July 1 & 2, 2013

Study emergent properties of matter with QCD degrees of freedom

Introduction to the Physics of High-Energy Nuclear Collisions

Nu Xu (1,2)

Many Thanks to Organizers!

(1) *College of Physical Science & Technology, Central China Normal University, Wuhan, 430079, China*

(2) *Nuclear Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*

Outline

7/1

I. Introductions

II. Status of the Relativistic Heavy Ion Collider

- Accelerator complex
- Detectors and future upgrades

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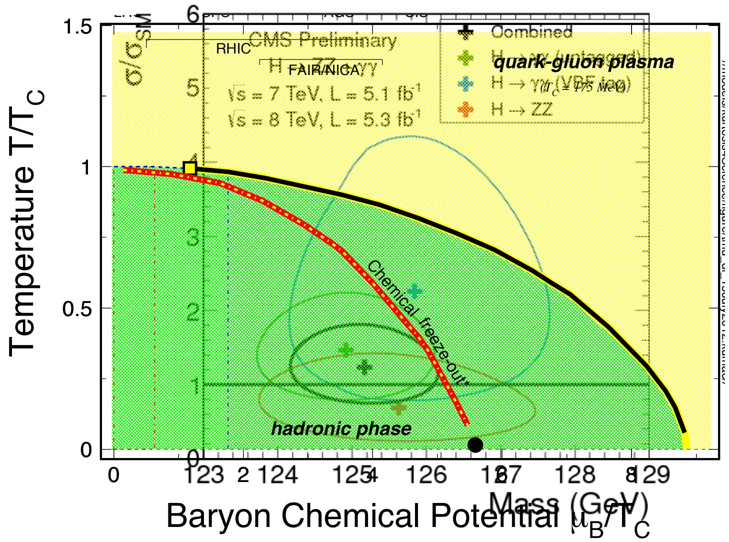
III. Transverse Dynamics in High-energy Nuclear Collisions

- Partonic collectivity
- Heavy flavor and the medium effects

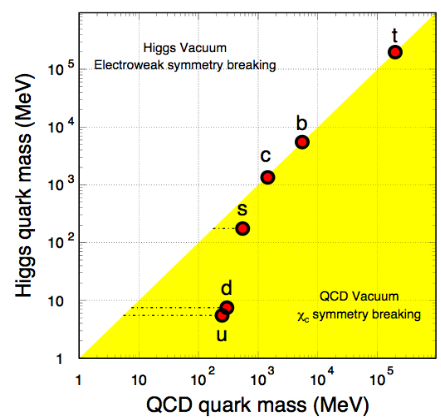
QCD in the Twenty-First Century

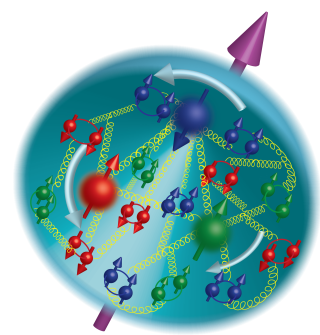


Emergent properties with QCD degrees of freedom!

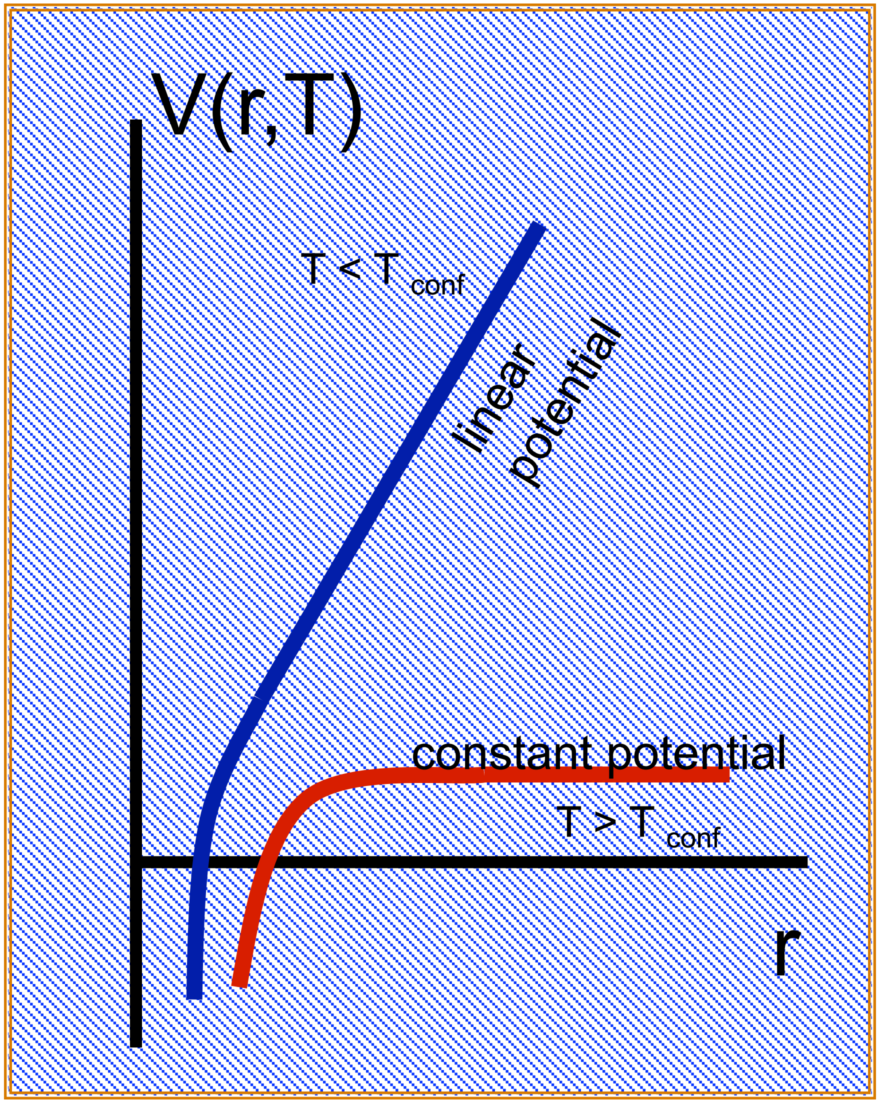
(1) Higgs (-like) Particle –
- **Origin of Mass**, **QCD dof**
- Standard Model ➔ The *Theory*

(2) QCD Emergent Properties:
- Confinement
- χ_C symmetry
- QCD Phase Structure
- Nucleon helicity structure
- Non-linear QCD at small-x





Confinement Potential



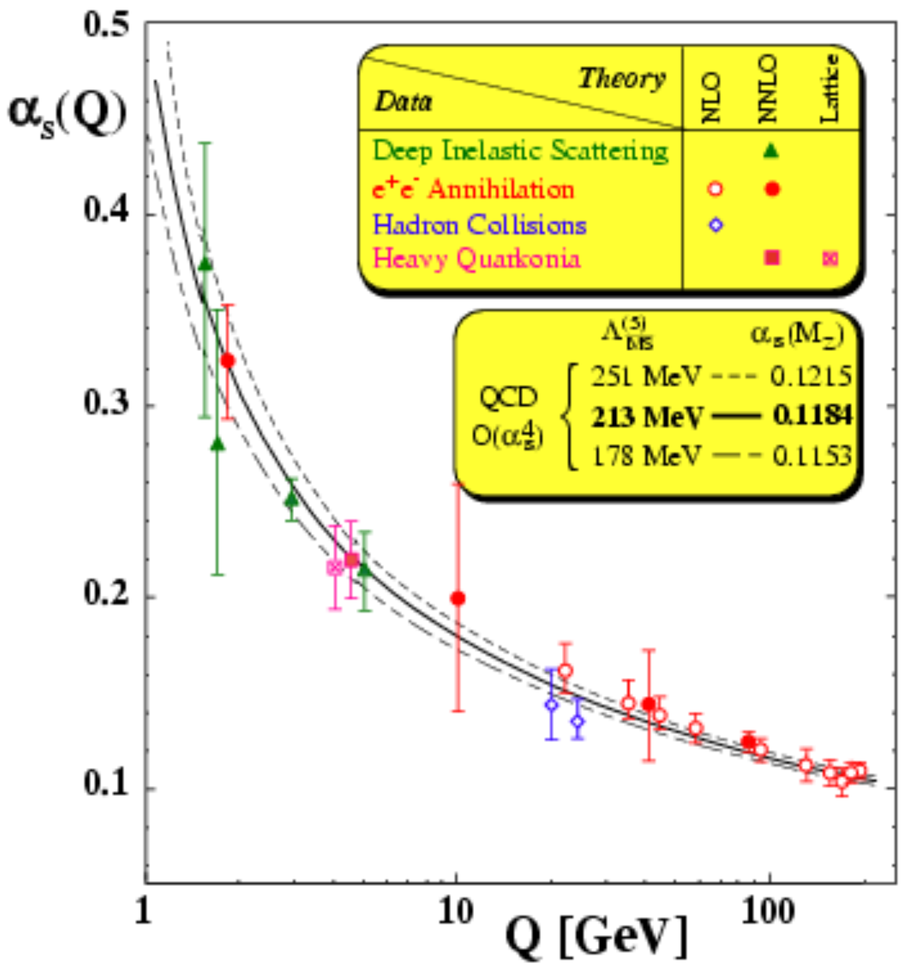
The potential between quarks is a function of distance. It also depends on
the temperature.

1) At low temperature, the potential increases linearly with the distance between quarks
⇒ quarks are confined;

2) At high temperature, the confinement potential is 'melted'
⇒ quarks are 'free'.

Note: It is not clear at all if there is a critical 'temperature' in high energy collisions

α_s vs. Q



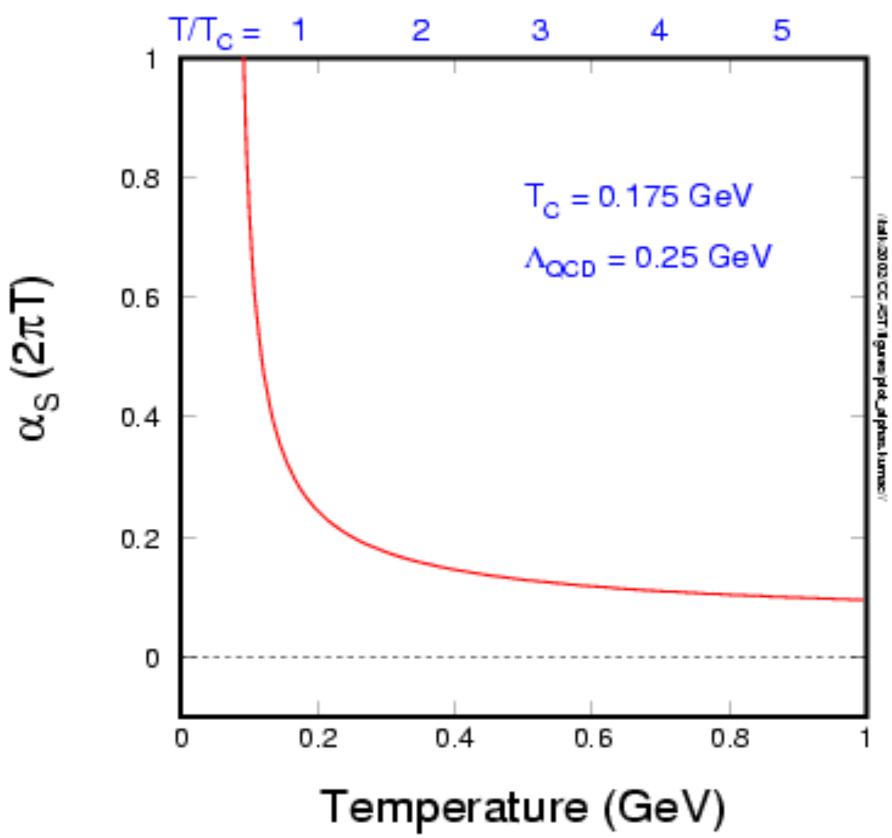
α_s: strong coupling constant
Q: momentum transfer

QCD models provide reasonable results on the Q-dependence of the strong coupling constant, especially at high Q.

As a function of the momentum transfer, the strong coupling constant α_s decreases exponentially, but never goes to zero, meaning STRONG interactions are always there!

Reference:
S.Bethke, hep-ex/0004021

Strong Coupling Constant α_S



$$\alpha_S \cong \frac{g_S}{4\pi} \propto \frac{1}{\ln(\mu^2/\Lambda^2_{QCD})}$$

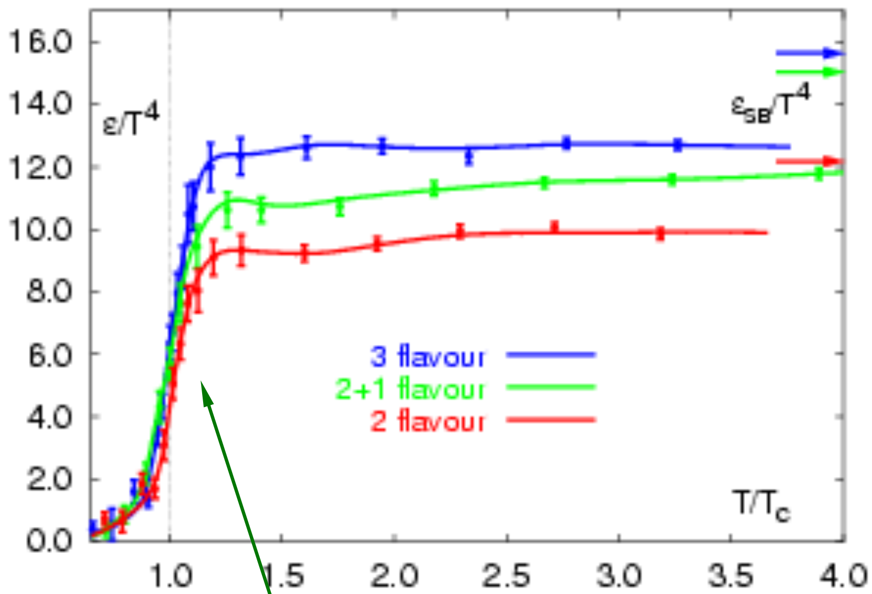
At high temperature, the coupling is ~ 0.1, not zero!

The finite value of α_S at high temperature leads to the observed collective mode on Lattice.

QED: similar picture of quasi Particles (Fermi liquid) : interaction of electrons with phones leads to higher effective electron mass.

No QGP of free quark gluon gas! Interactions (though small) and ***collective modes*** are important!

QCD on Lattice



Lattice calculations predict
$T_C \sim 170$ MeV

1) Large increase in ε
a fast cross cover !

2) Does not reach ideal, non-interaction S. Boltzmann limit !

⇒ many body interactions

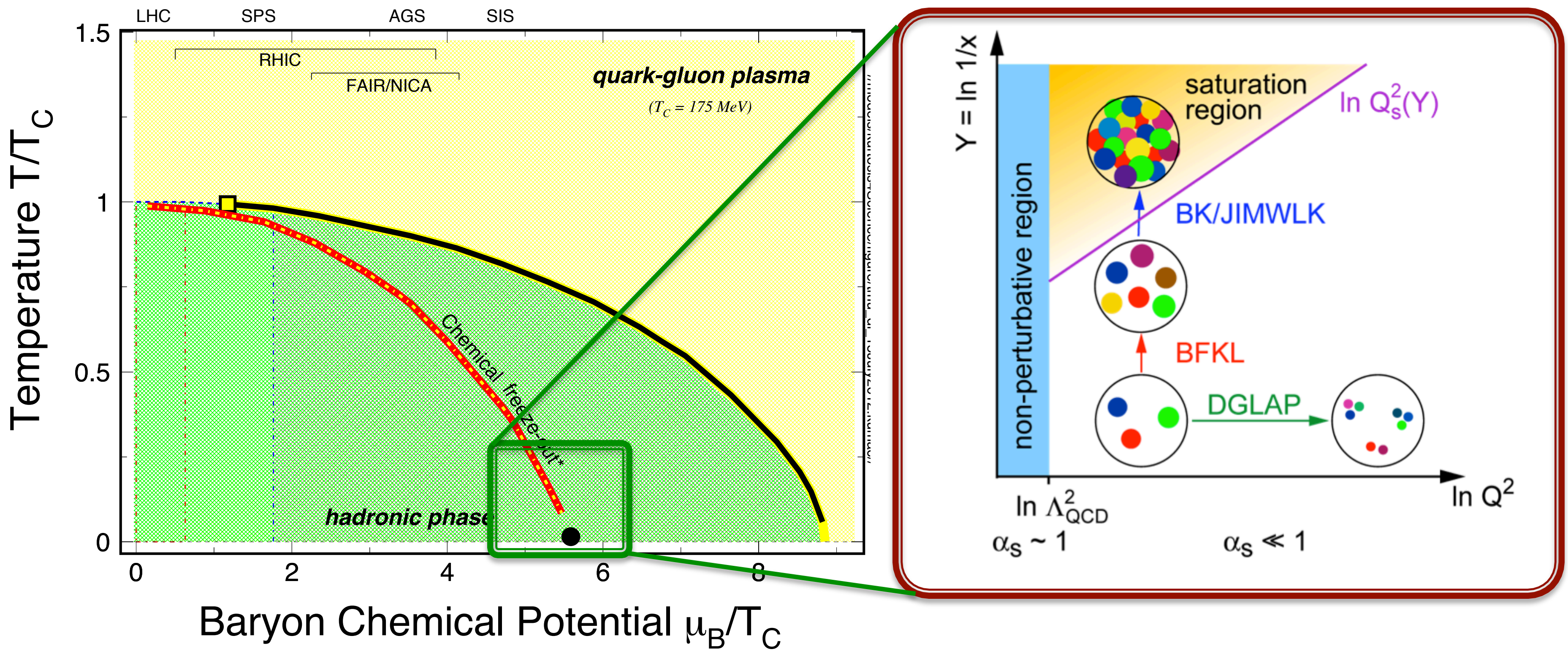
⇒ Collective modes

⇒ Quasi-particles are necessary

3) $T_C \sim 170$ MeV robust!

*Z. Fodor et al, **JHEP** 0203:014(02)*
Z. Fodor et al, hep-lat/0204001
C.R. Allton et al, hep-lat/0204010
F. Karsch, Nucl. Phys. A698, 199c(02).

QCD Phase Structure



RHIC/LHC (Hot QCD)

EIC (eRHIC) (Cold QCD)

Study phase structure with the QCD degrees of freedom

Outline

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   - Accelerator complex
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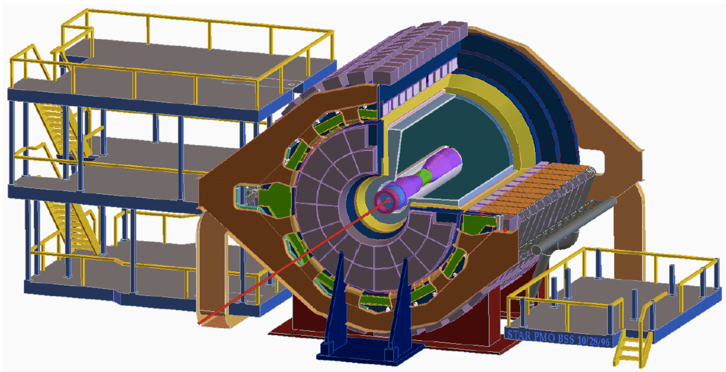
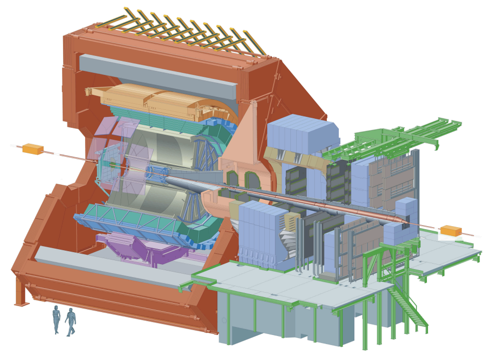
   - Partonic collectivity
   - Heavy flavor and the medium effects

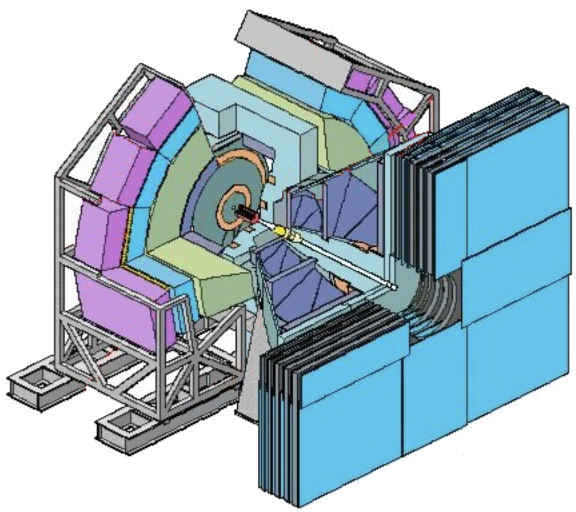
High-Energy Nuclear Collider Experiments



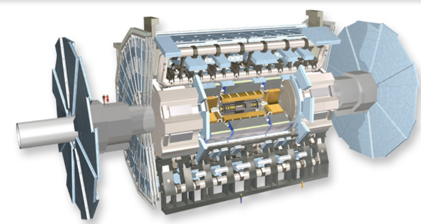
STAR (Solenoidal Tracker At RHIC)



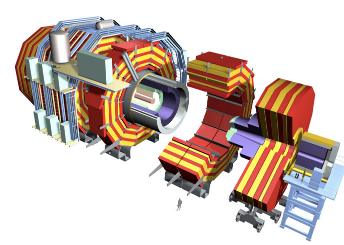
ALICE (A Large Ion Collider Experiment)



PHENIX (Pioneering High Energy Nuclear Ion Experiment)



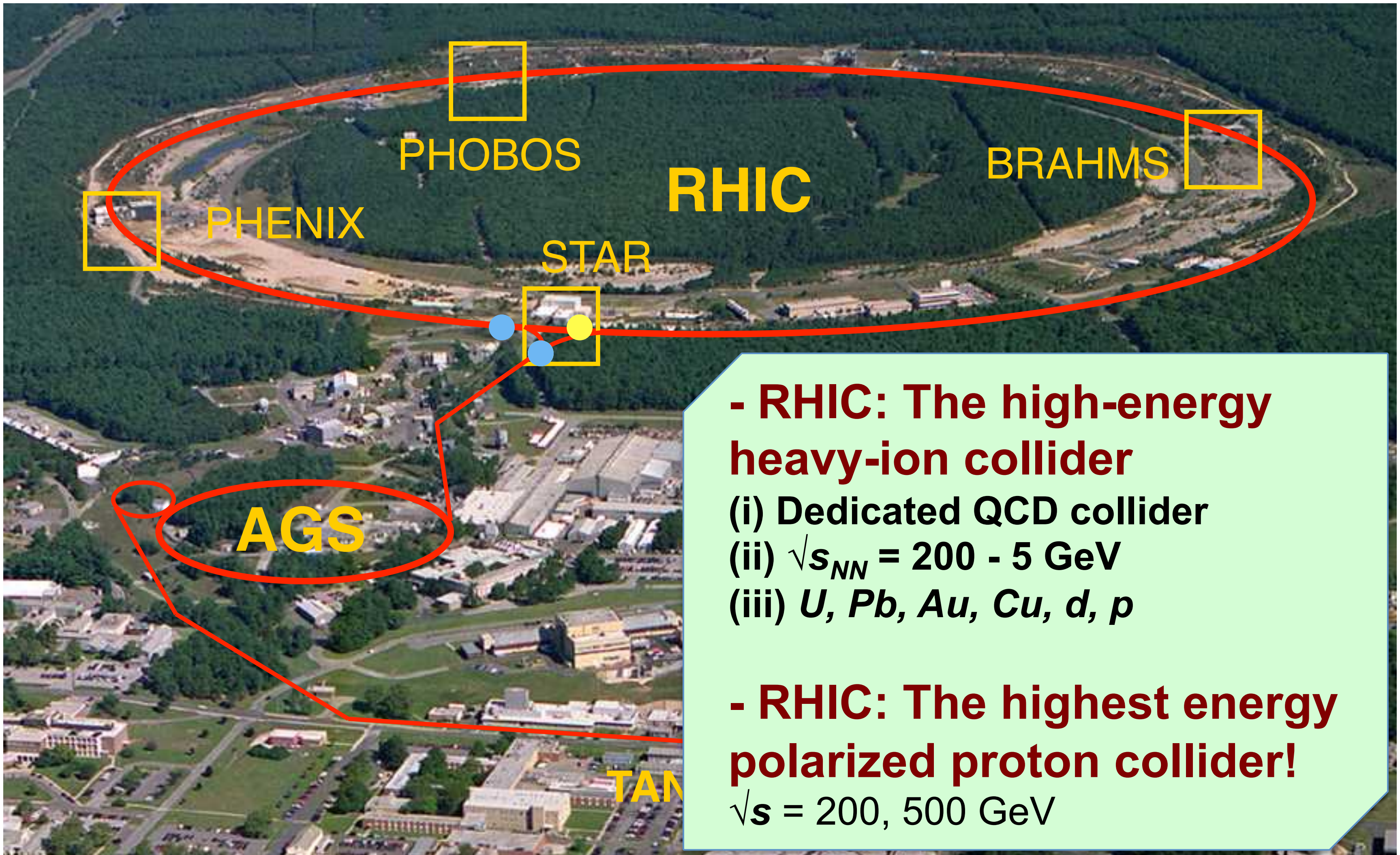
ATLAS (A Toroidal LHC Apparatus)



CMS (Compact Muon Solenoid)

Relativistic Heavy Ion Collider

Brookhaven National Laboratory (BNL), Upton, NY



- **RHIC: The high-energy heavy-ion collider**

(i) Dedicated QCD collider
(ii) $\sqrt{s_{NN}}$ = 200 - 5 GeV
(iii) *U, Pb, Au, Cu, d, p*

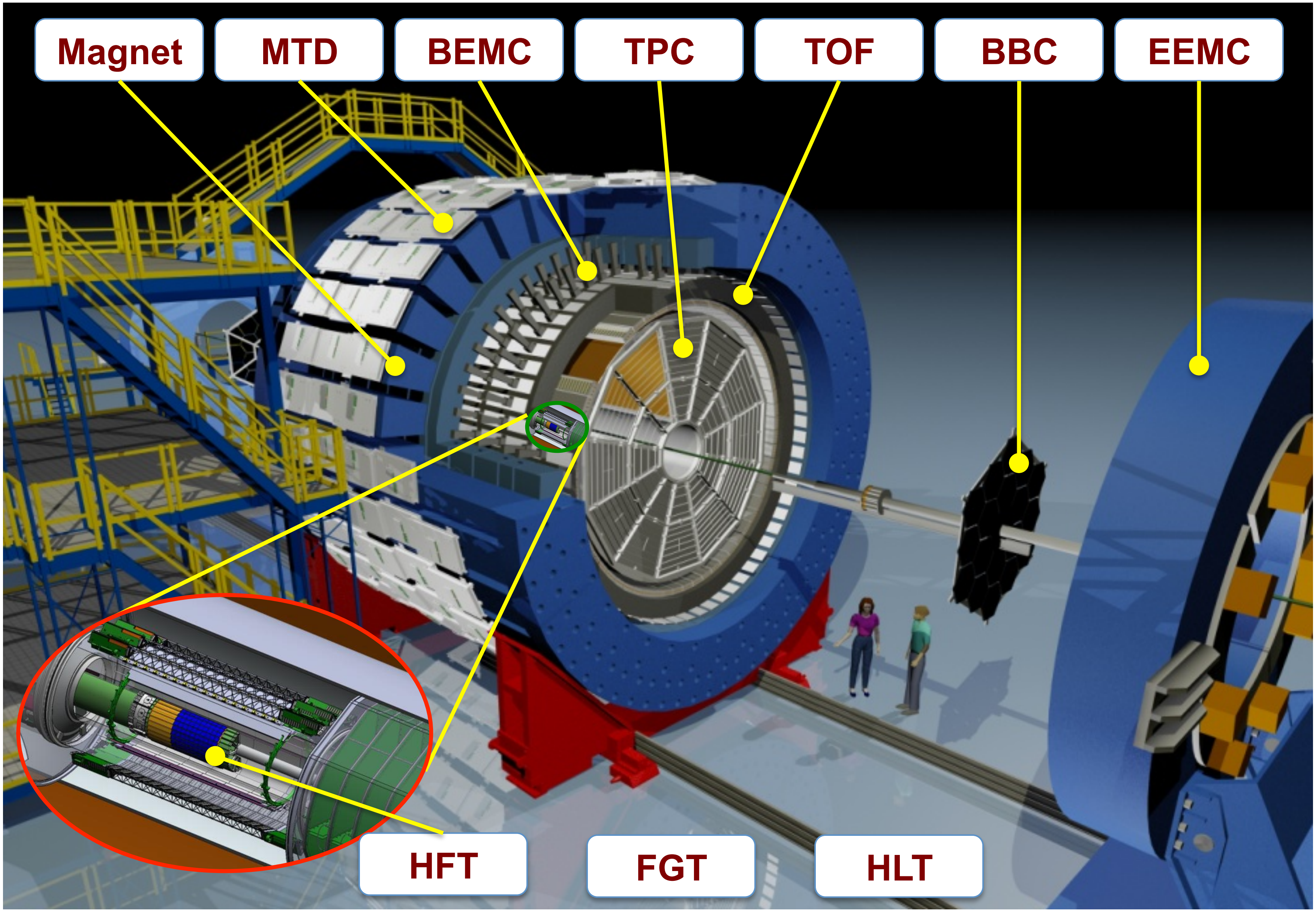
- **RHIC: The highest energy polarized proton collider!**

$\sqrt{s}$ = 200, 500 GeV

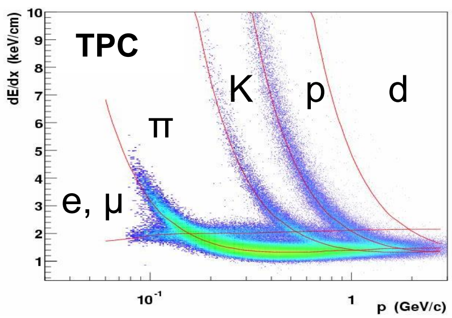
Animation M. Lisa

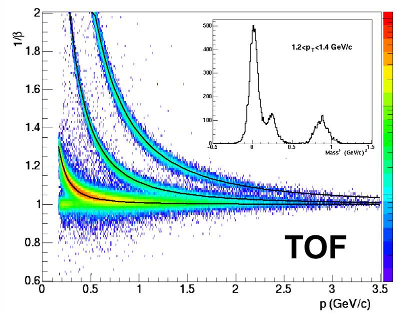

STAR Collaboration
CAP.
4000
DREXEL

STAR Experiment

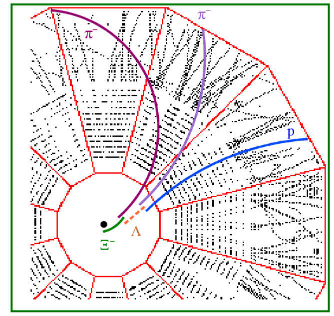


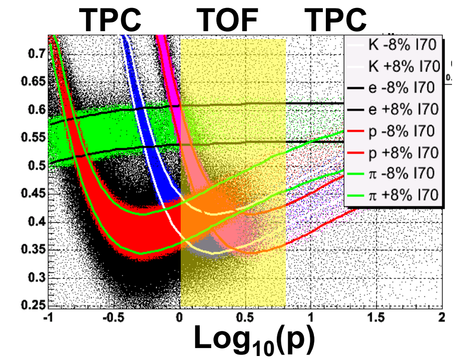
Particle Identification at STAR



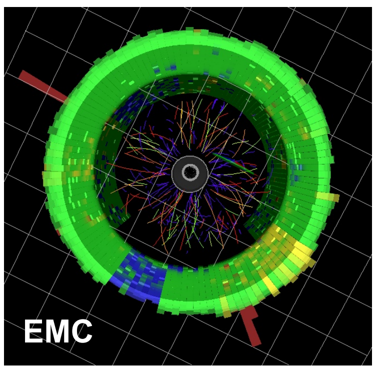


Charged hadrons

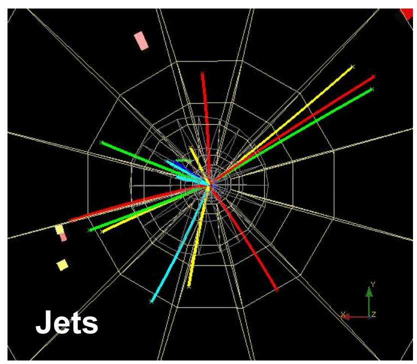




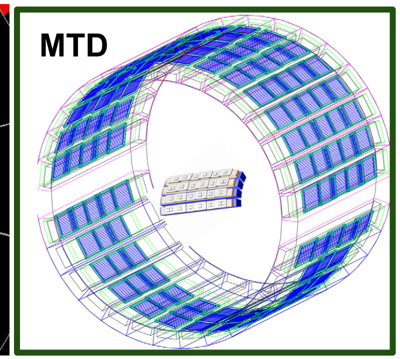
Hyperons & Hyper-nuclei



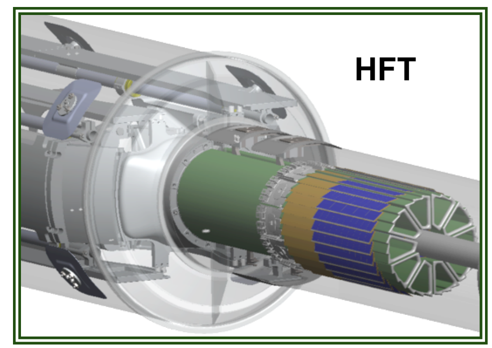
Neutral particles



Jets & Correlations



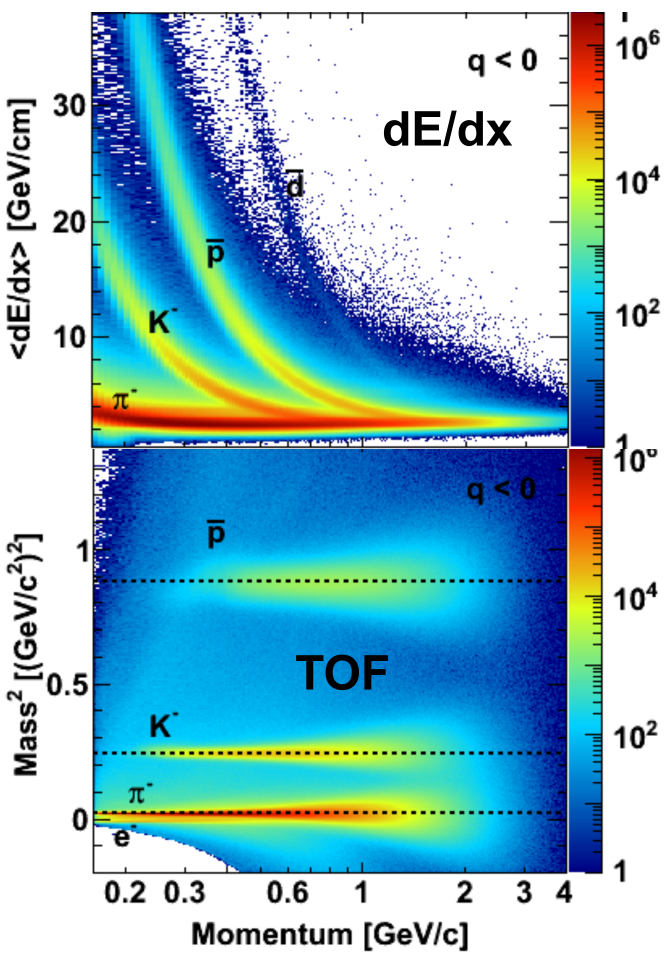
High p_T muons

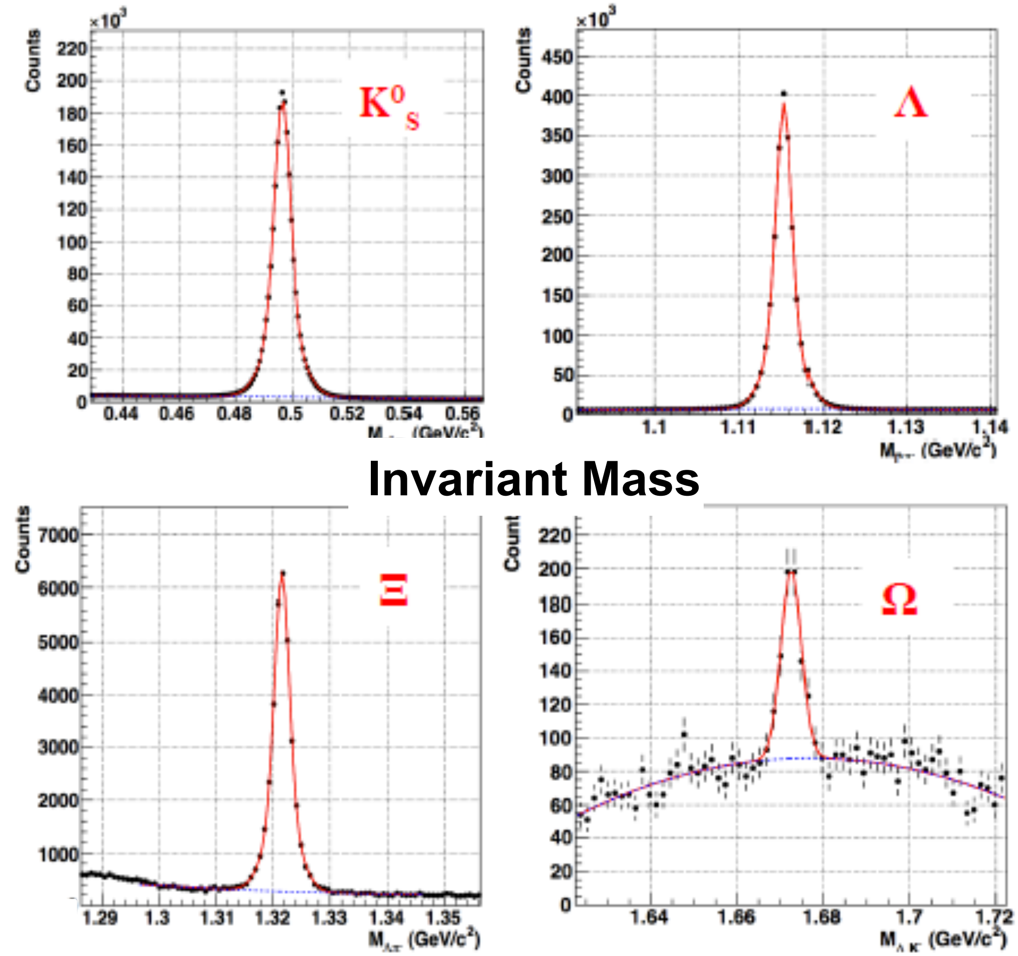


Heavy-flavor hadrons

Multiple-fold correlations for the identified particles!

Particle Identification

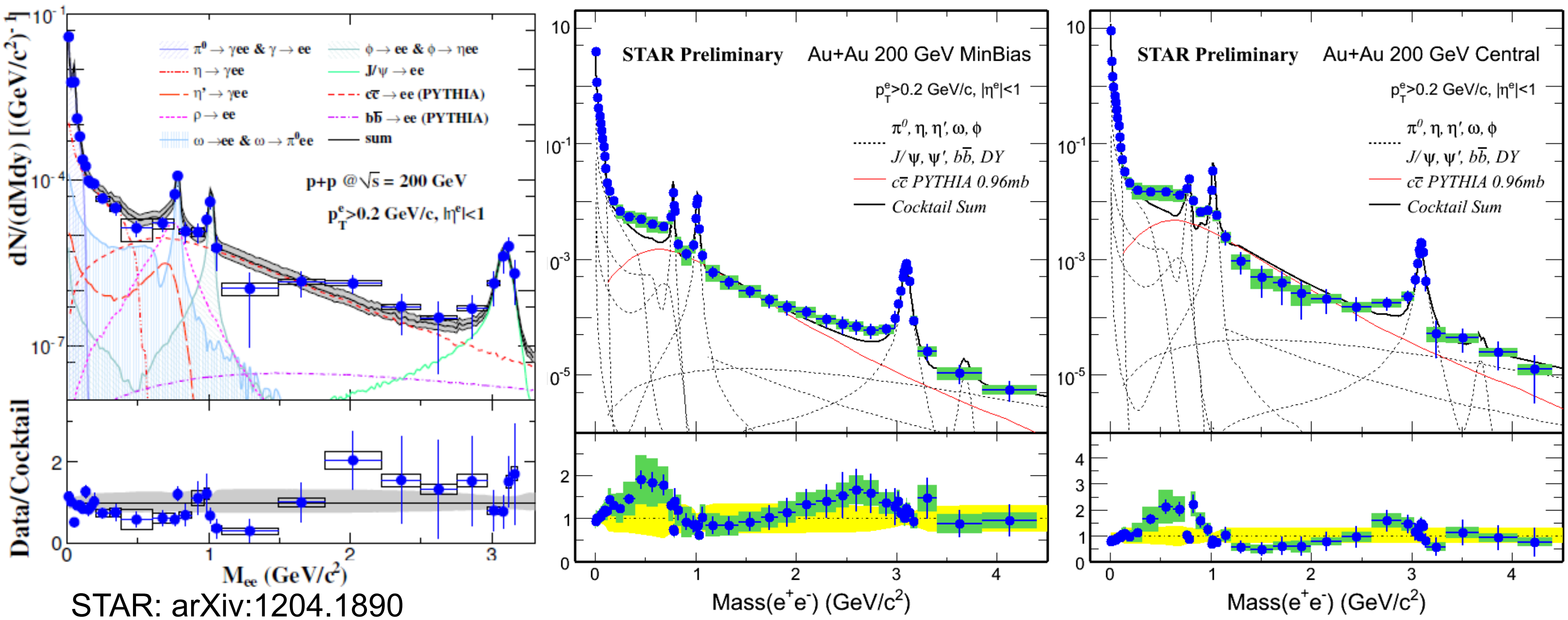




STAR Detector: Large uniform acceptance; Excellent PID

Di-lepton: Penetrating-Bulk Probe

√s = 200 GeV **p+p** **Au+Au MinBias** **Au+Au Central**



STAR: arXiv:1204.1890

1) Direct radiation, ***penetrating-bulk probe***
2) Beam energy, p_T, centrality, mass dependence (8-10x more events):
   R_{AA}, v_2, radial expansion, HBT, polarization, …
3) HFT/MTD upgrades: key for the correlated charm contributions.

STAR Detector Configurations

	Period	Detectors	Physics
	2001-2010	**TPC**	*u, d, s*
	2010	TPC + TOF	*u, d, s + dilepton*
	2013	TPC + TOF + MTD	*u, d, s, c, b + dilepton*
	2014	TPC + TOF + MTD **+ HFT**	

→ STAR: Large coverage, excellent PID, fast DAQ

- detects nearly all particles produced at RHIC
- multiple fold correlation measurements
- **Probes: bulk, penetrating, and *bulk-penetrating***

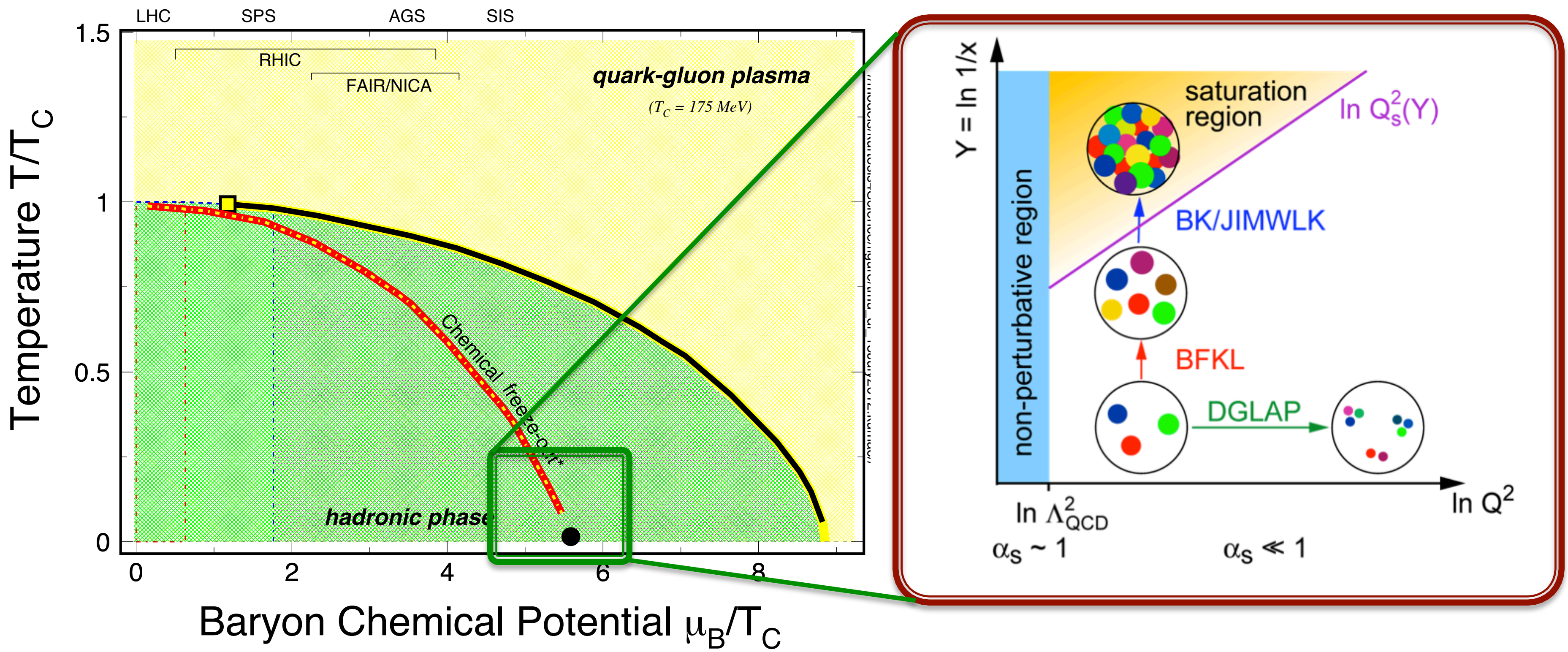
→ STAR: An excellent mid-y collider experiment

→ STAR: Expanding into forward rapidity regions

QCD Phase Structure

Hot QCD Matter

Cold QCD Matter

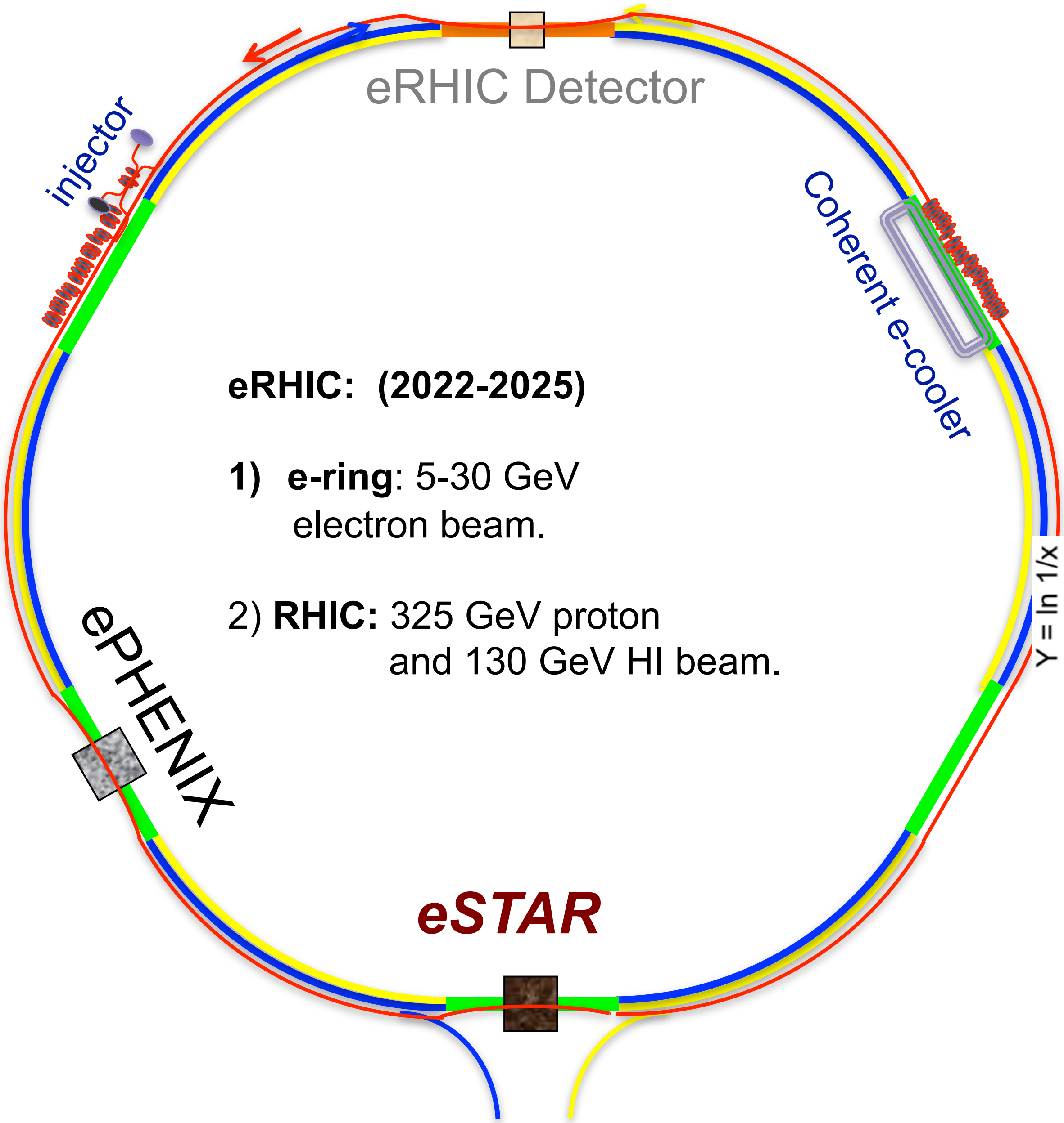


RHIC/LHC

EIC (eRHIC)

Study phase structure with QCD degrees of freedom

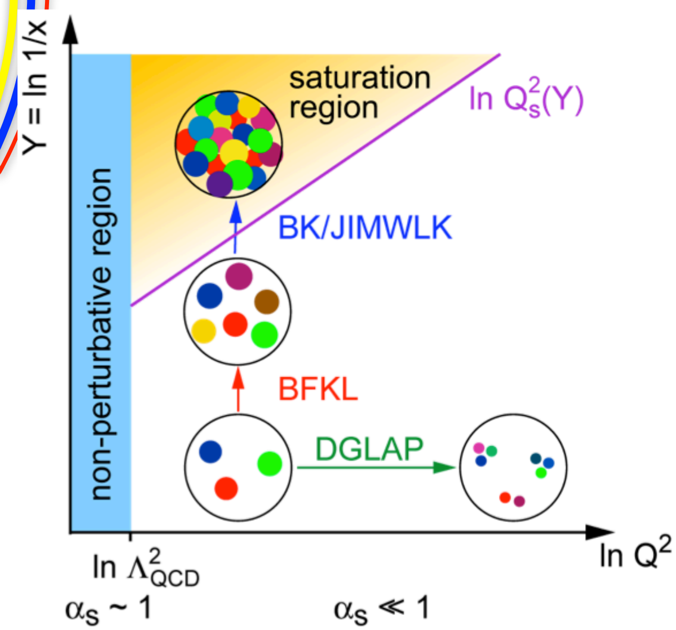
Electron Ion Collider (eRHIC)



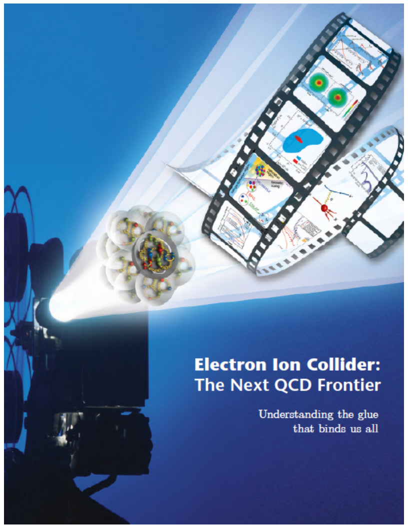
eRHIC: (2022-2025)

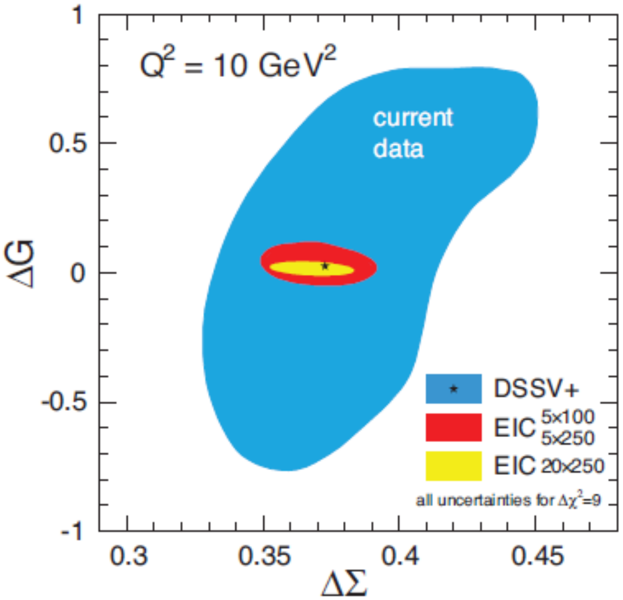
1) e-ring: 5-30 GeV electron beam.

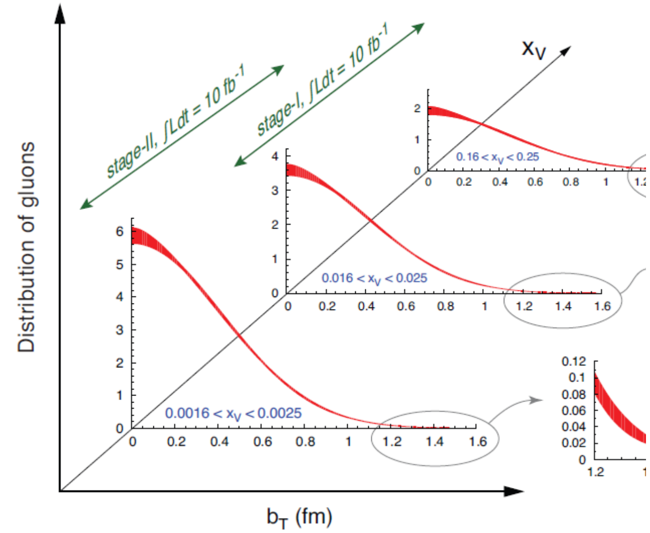
2) **RHIC:** 325 GeV proton and 130 GeV HI beam.

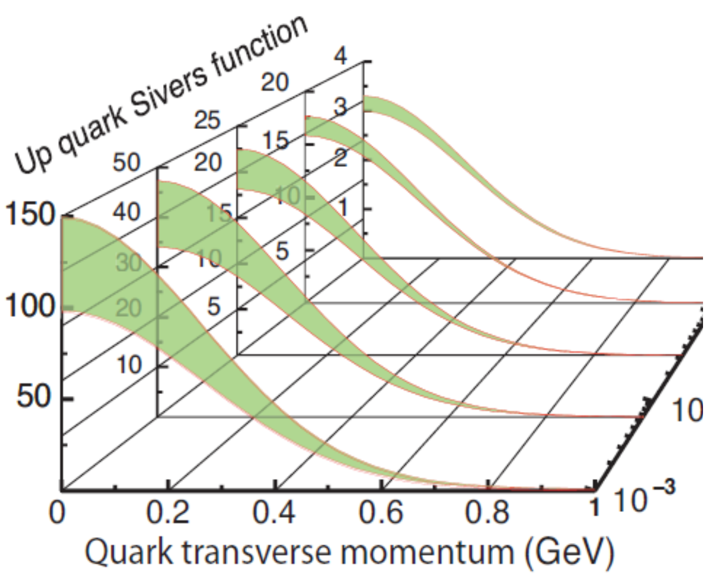


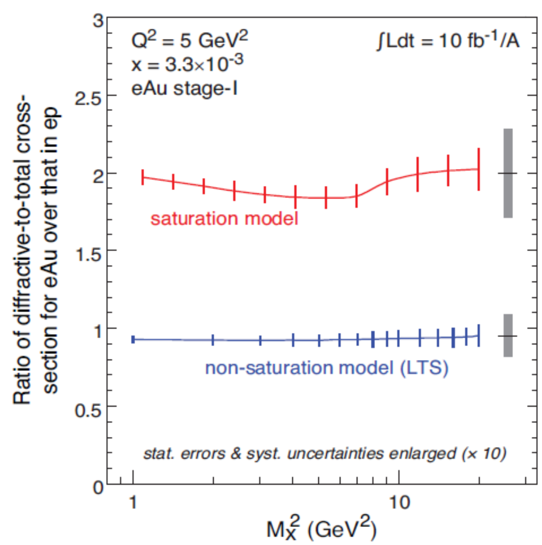
eRHIC Physics

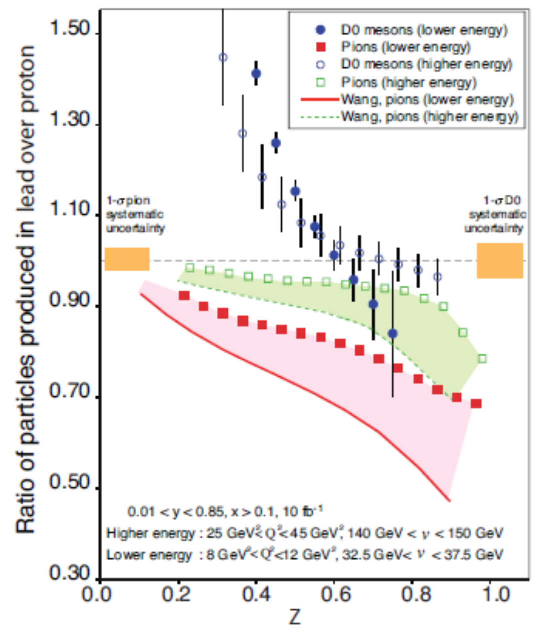




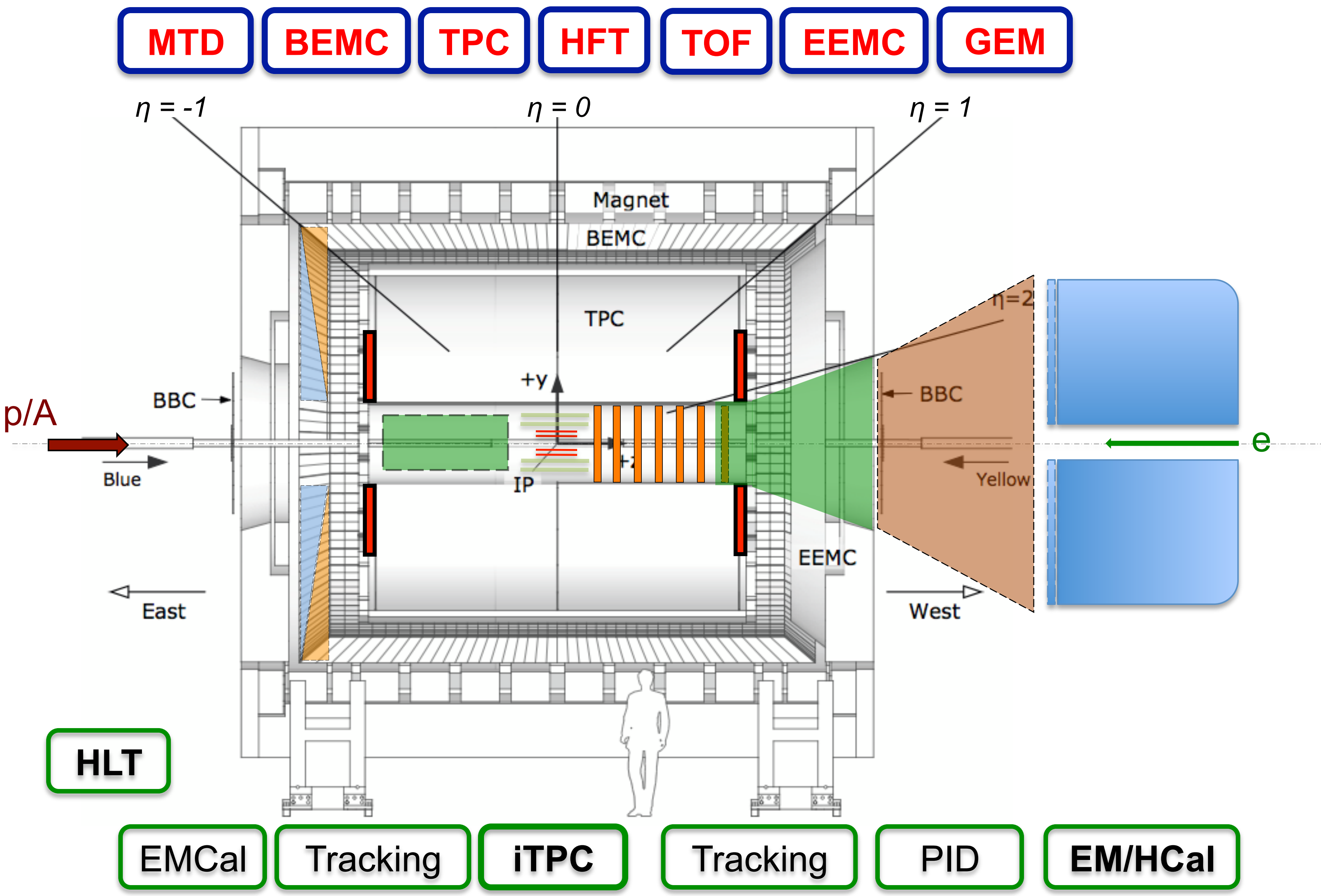








STAR Forward Upgrade Plan (~2018)

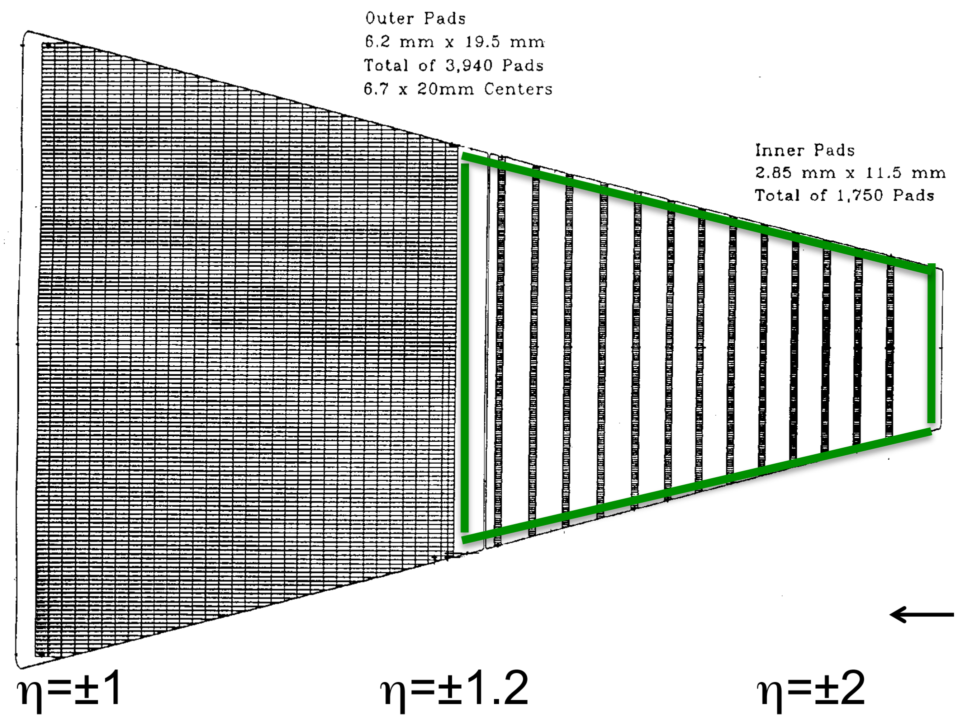


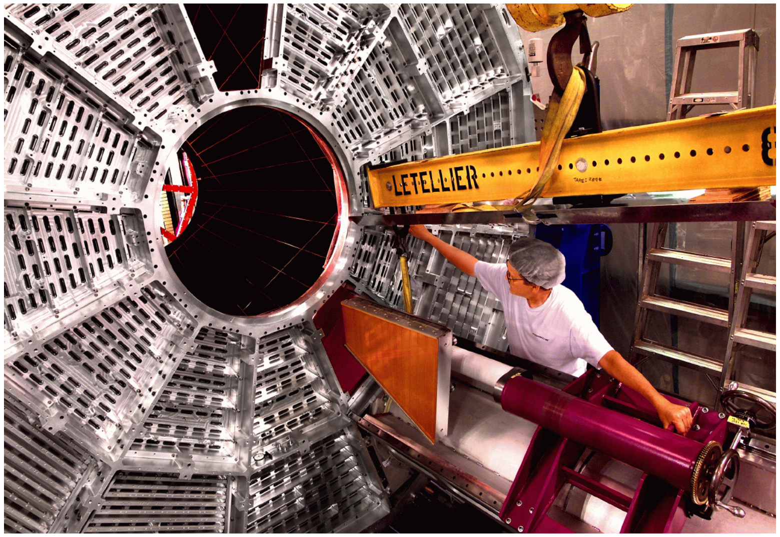
TPC Inner Sector Upgrade (iTPC)

- Staggered readout
  - Only 13 maximum possible points
    - Issues in Tracking: recognition and resolution
  - Only reads ~20% of possible gas path length
    - Inner sectors essentially not used in dE/dx
- Essentially limits TPC effective acceptance to |η|<1

iTPC Upgrade:

1. MWPC (SDU/SINAP)
   ATLAS sTGC
   Chinese 973 project
2. Mechanics (LBL/BNL)
   Eric Anderson (PI)
3. Electronics (BNL/ALICE)
4. Schedule (2017)

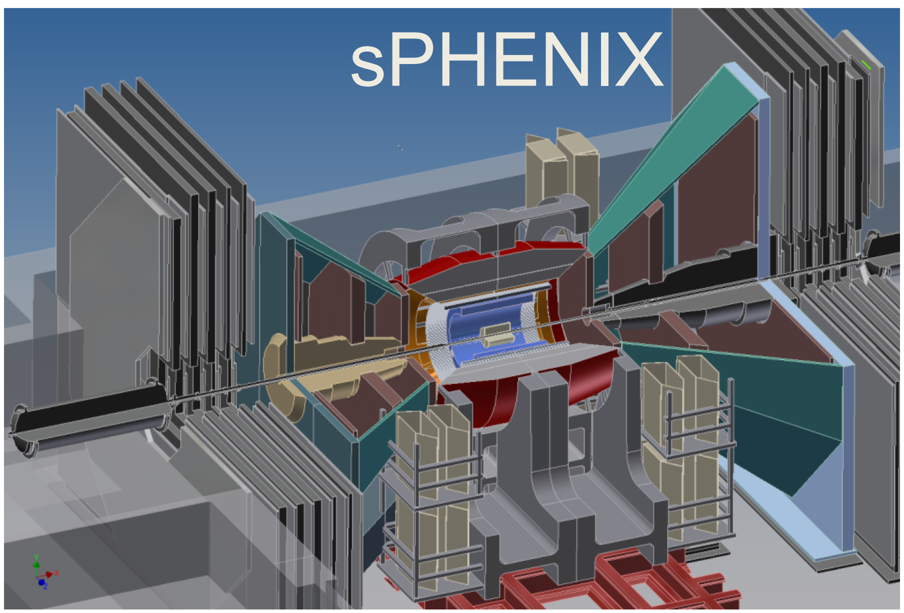


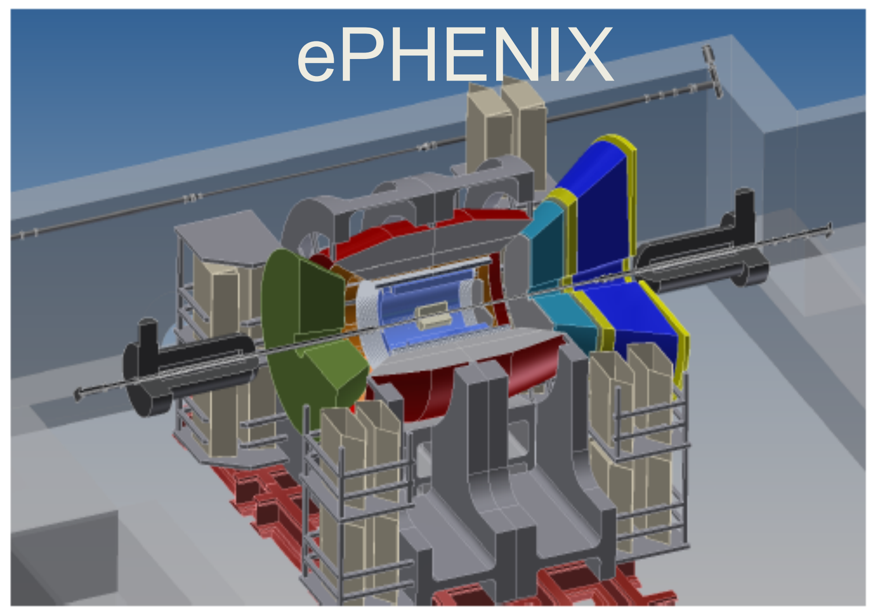


PHENIX: sPHENIX & ePHENIX

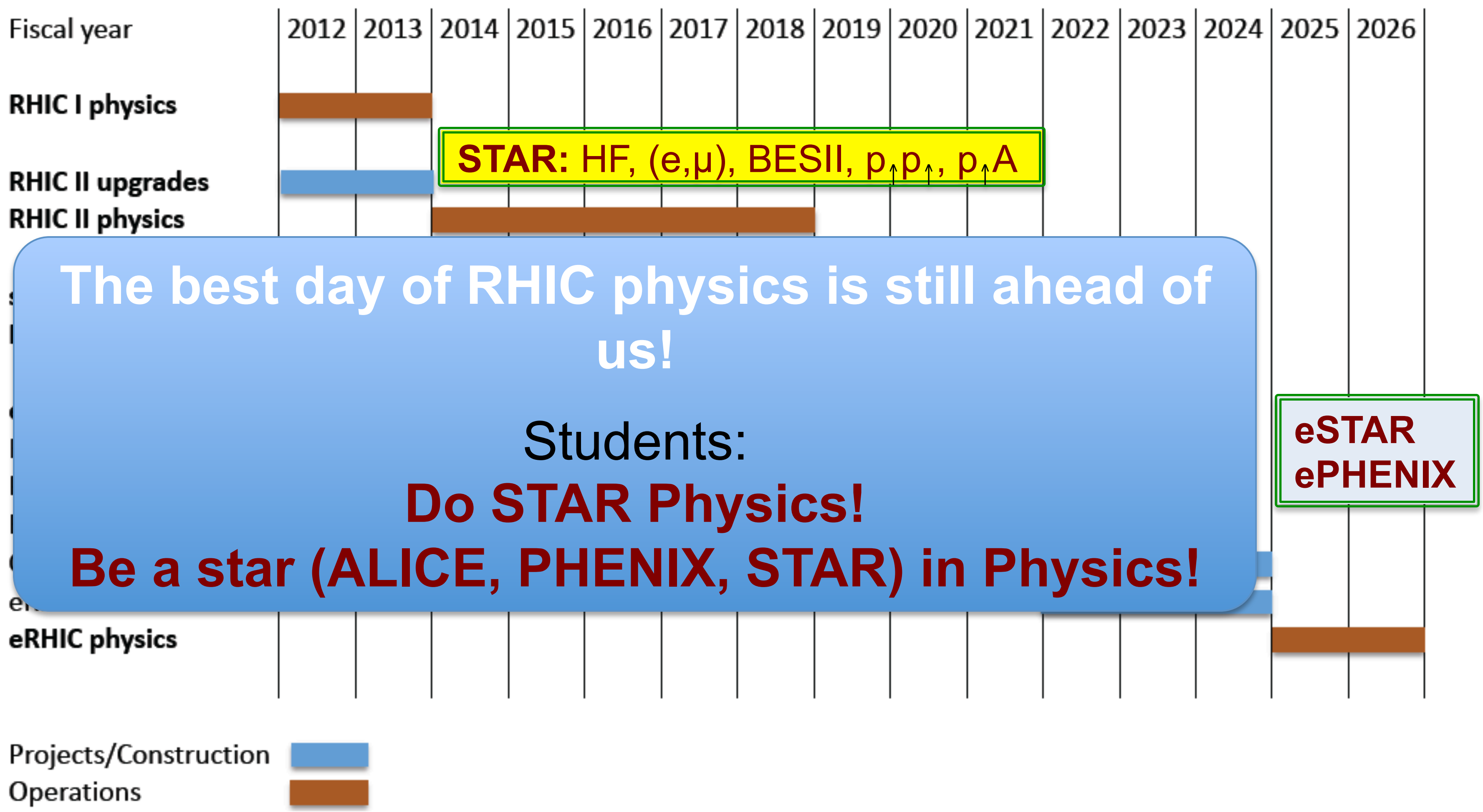
1) Major changes in PHENIX detector underway: Lepton, photon dominant => Full jets measurements at RHIC: sPHENIX

2) Greatly increased acceptance (x20-50 in many channels) and key new detector capabilities





RHIC: Upgrade Plan (now - 2025)

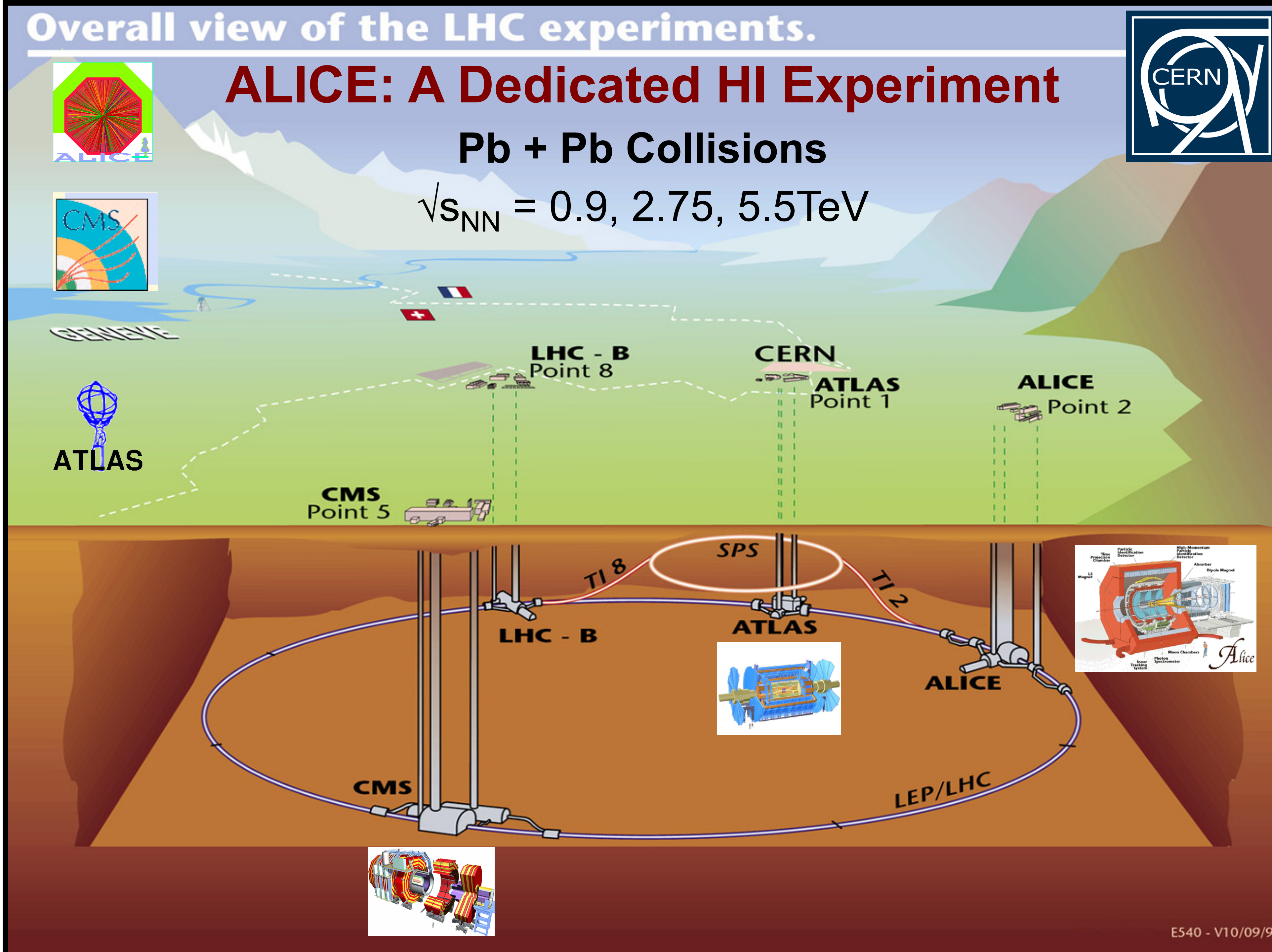


The best day of RHIC physics is still ahead of us!
More efforts needed for pA and ep/eA physics programs!

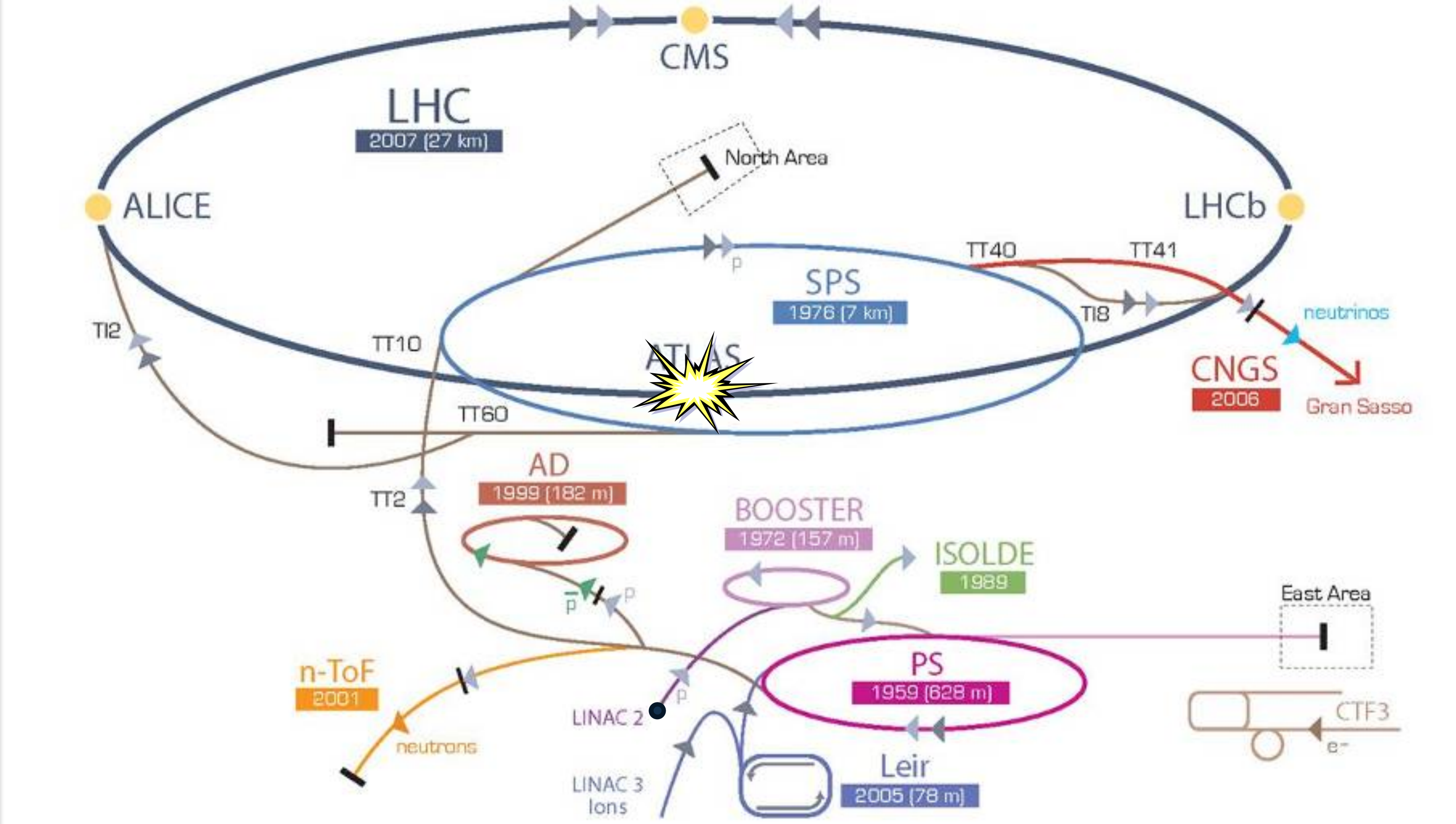
ALICE: A Dedicated HI Experiment

Pb + Pb Collisions

$\sqrt{s_{NN}}$ = 0.9, 2.75, 5.5TeV

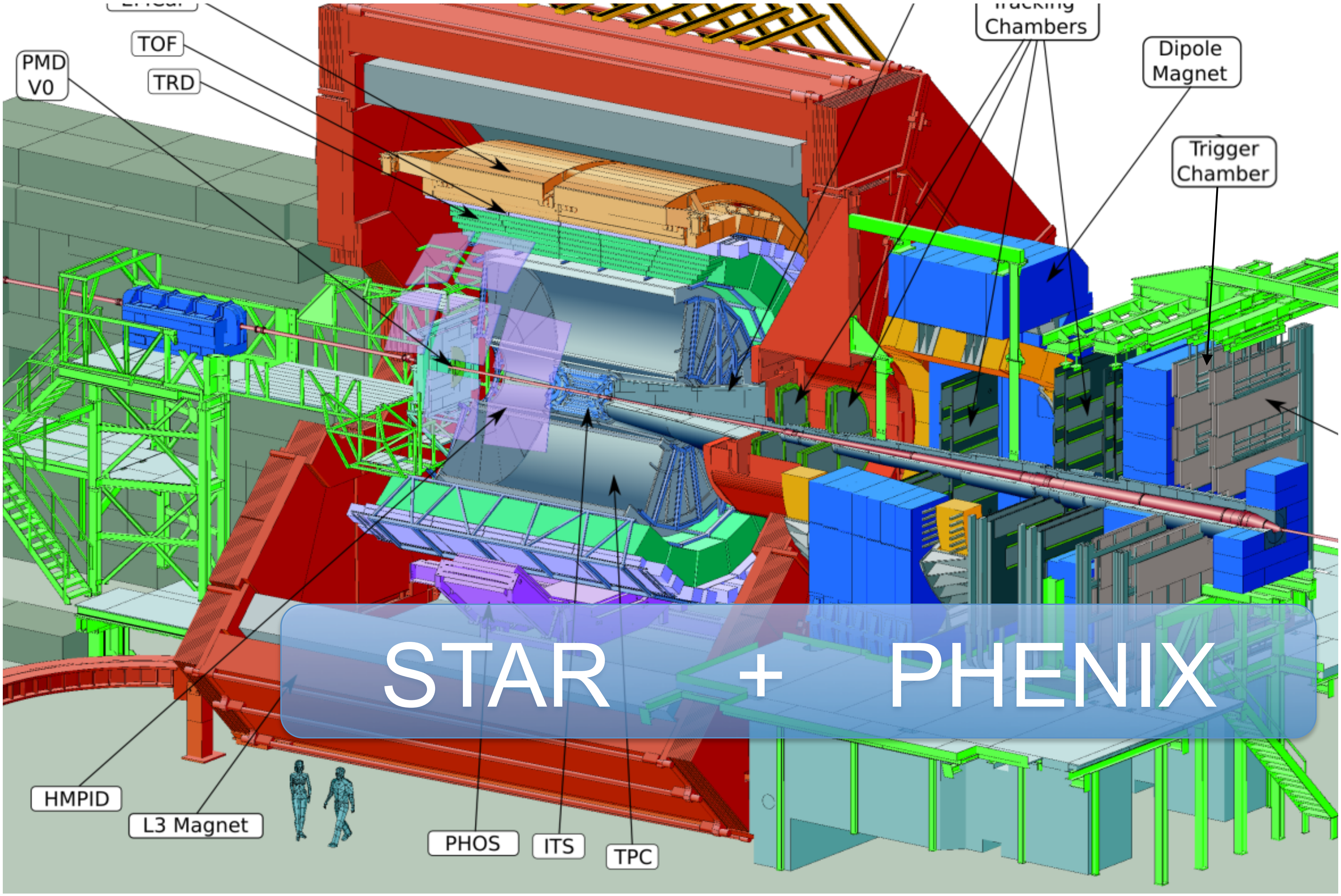


Large Hadron Collider

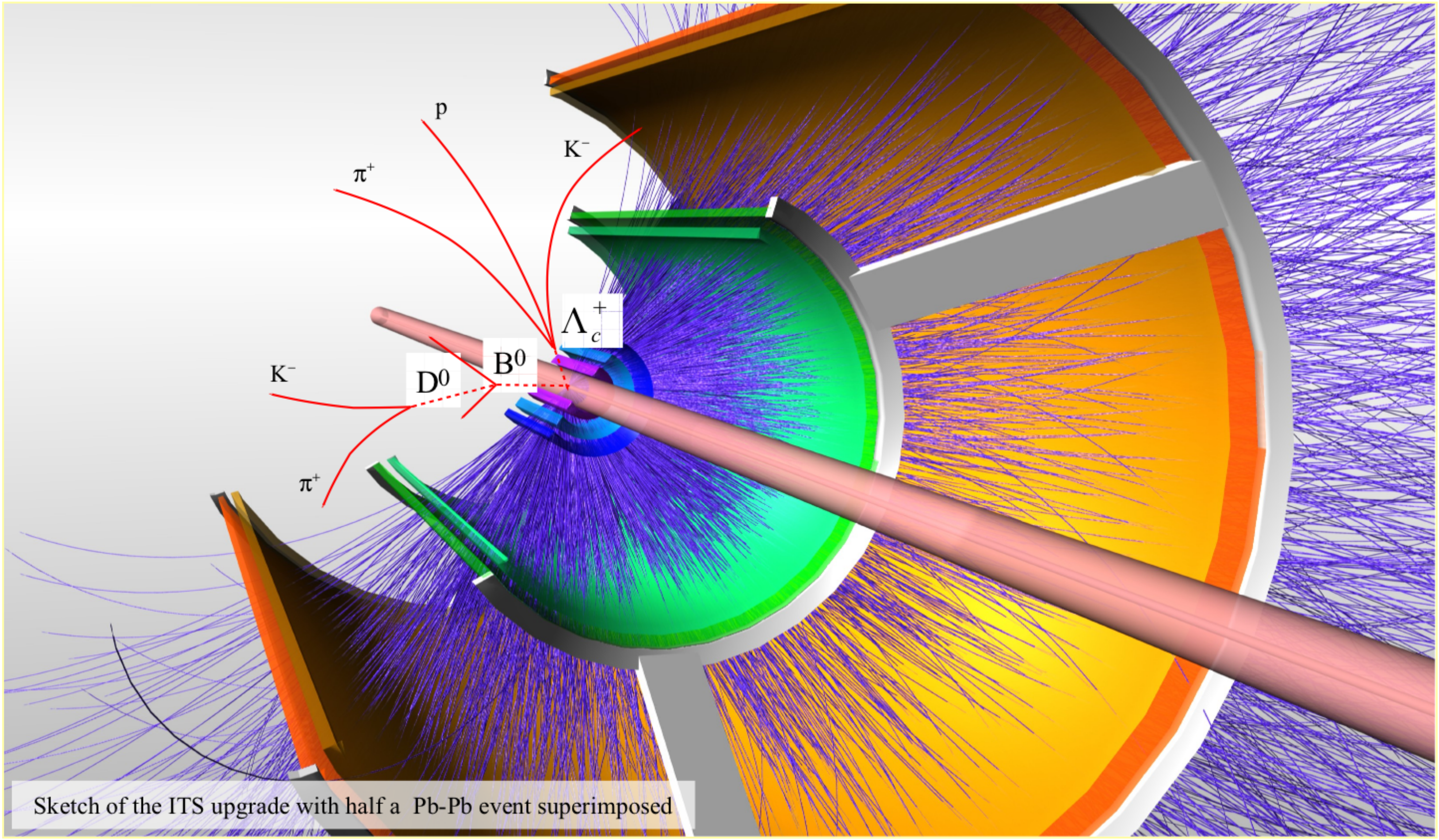



Long term issues have
been arranged!

ALICE Experiment



Upgrading the Inner Detector



Sketch of the ITS upgrade with half a Pb-Pb event superimposed

- upgrade Concept recently approved by the ALICE Collaboration
- targeted for 2017-2018 LHC shutdown
  Erice, 34th Course
- Conceptual Design Report CERN-LHCC-2012-005

Future Trends in High-Energy Nuclear Collisions

August 19 – 22, 2013
Beijing, China

Organizing Committee:

Harry Appelshaeuser (Frankfurt University, Germany)
Jianwei Qiu (BNL,USA)
Daicui Zhou (CCNU, China)
Barbara Jacak (Stony Brook University, USA)
Nu Xu (CCNU/LBNL, China/USA)
Pengfei Zhuang, chair (Tsinghua University, China)

Workshop website: http://qm.phys.tsinghua.edu.cn/thu-henp/2013/index.html

Physics about LHC, RHIC, and eRHIC will be discussed at the workshop. **Limited funds are available to support young scientists.** The funds will cover the registration fee and local expenses. For those who are interested please send their applications to Prof. Pengfei Zhuang, zhuangpf@mail.tsinghua.edu.cn, by July 31, 2013.

Future Trends in High-Energy Nuclear Collisions

August 19 – 22, 2013
Beijing, China

Invited Workshop Speakers

ALICE Experiment:
- Jets and photons: Christian Klein-Boesing (University Muenster)
- Detector development for ALICE upgrade: Luciaino Musa (CERN)
- Quarkonia and heavy flavors: Andrea Dainese (INFN Padua
- p+Pb results from ALICE: Constantin Loizides (LBNL)
- Bulk results from ALICE: Jan Fiete Grosse-Oetringhaus (CERN)
- Physics program of ALICE upgrade: K. Safarik (CERN)

PHENIX Experiment:
- RHIC jets: Barbara Jacak (Stony Brook University)
- RHIC quarkonia: Xiaochun He (Georgia State University)
- RHIC photons and dileptons: Yasuyuki Akiba (RIKEN)
- RHIC initial state and d/p+A: Richard Seto (UC Riverside)
- RHIC spin: Jin Huang (LANL)
- sPHENIX upgrade plans: Dave Morrison (BNL)
- Forward s/ePHENIX upgrade plans: Kieran Boyle (BNL)
- PHENIX R&D: Tom Hemmick (Stony Brook University)

Future Programs and Summary:
- EIC physics program: Abhay Deshpande (Stony Brook University)
- EIC in China: Xurong Chen (IMP)
- Workshop Summary: Jianwei Qiu (BNL)

STAR Experiment:
- Bulk measurements at RHIC: Xianglei Zhu (Tsinghua University)
- Freeze-out studies at RHIC: Daniel Cebra (UC Davis)
- Beam Energy Scan Program: Xin Dong (LBNL)
- Open heavy flavor measurements: Yifei Zhang (USTC)
- STAR future R&D: Zhangbu Xu (BNL)
- RHIC exotica: Aihong Tang (BNL)
- eSTAR program: Ernst Sichtermann (LBNL)

Theory:
- Future of High-Energy Nuclear Collisions: Berndt Mueller (BNL/Duke)
- CGC, Glassma: Larry McLerran (BNL)
- Di-lepton Emission in HI Colisions: Ralf Rapp (Texam A&M)
- Pre-Equilibrium: Jinfeng Liao (Indiana University)
- Small-x Physics in pp/pA Collisions: Feng Yuan (LBNL)
- Jet-Quenching in HI Collisions: Xin-Nian Wang (CCNU/LBNL)
- Quarkonia Production in HI Collisions: Pengfei Zhunag (Tsinghua University)
- Transport Approach: Zhe Xu (Tsinghua University)
- Hydrodynamics: Tetsufumi Hirano (Sophia University)
- Transport in HI: Hannah Petersen (Frankfurt University)

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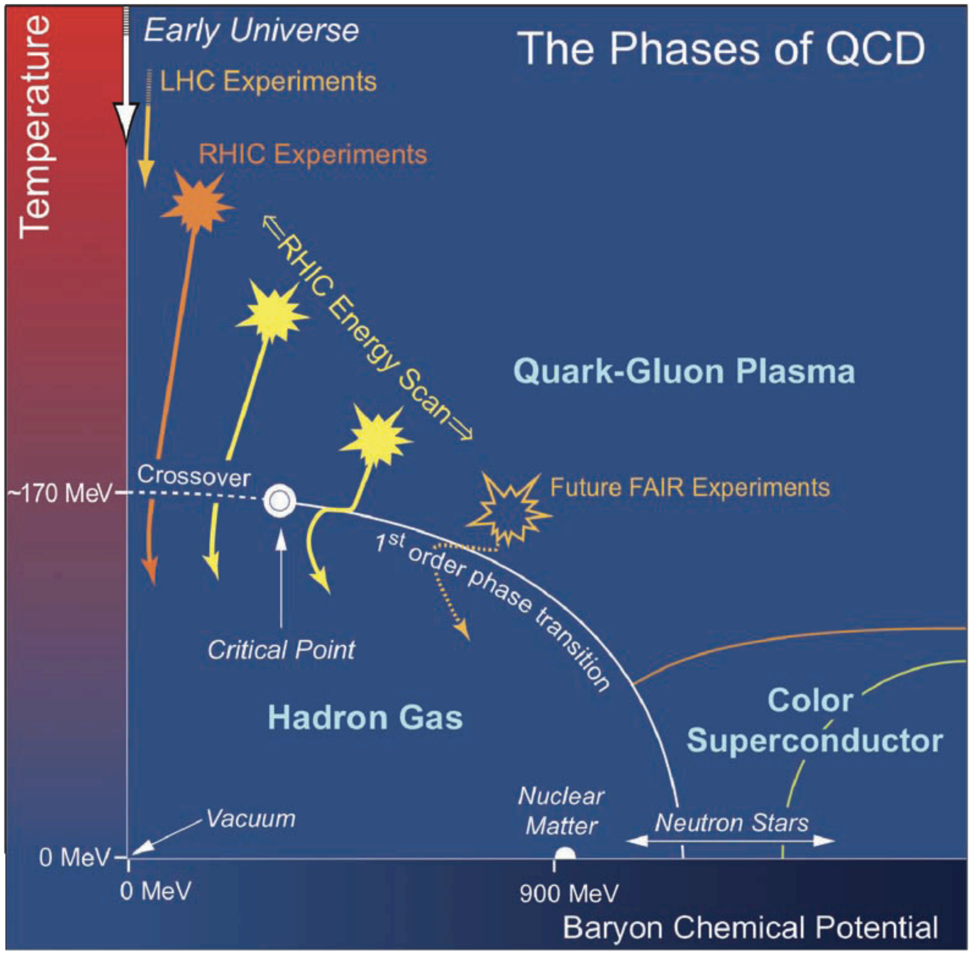
Beam Energy Scan at RHIC

Study QCD Phase Structure
- Signals of phase boundary
- Signals for critical point



Observations:

(1) Azimuthally HBT
1st order phase transition

(2) Directed flow v_1
1st order phase transition

(3) Dynamical correlations
partonic vs. hadronic dof

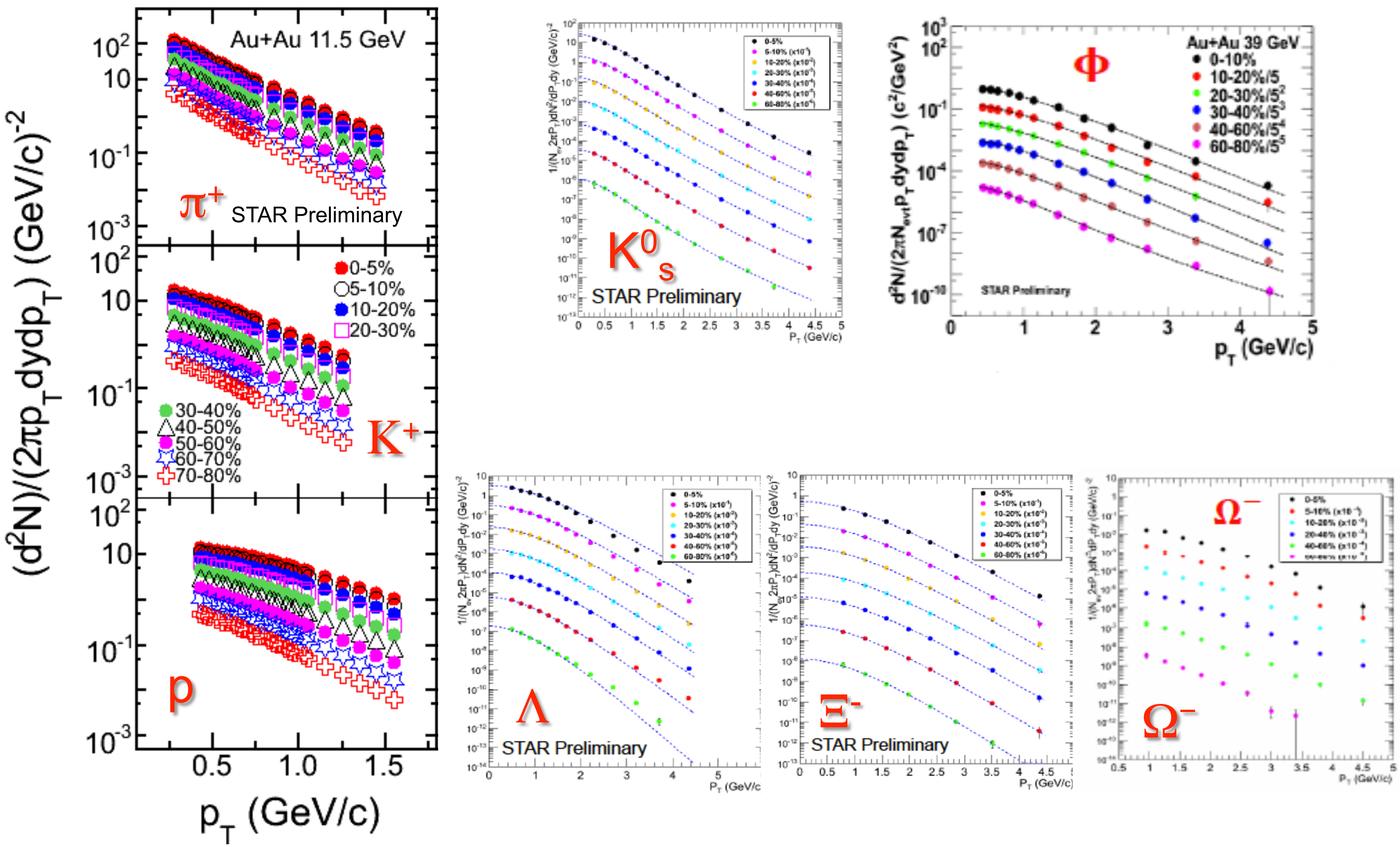
(4) v_2 - NCQ scaling
partonic vs. hadronic dof

(5) Fluctuations
Critical point, correl. length

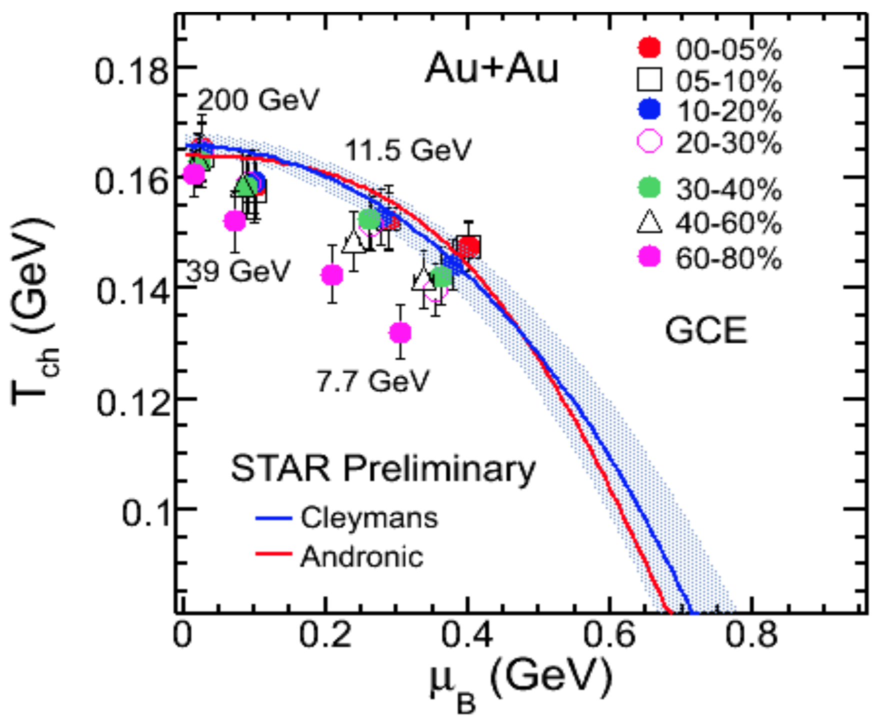
- *http://drupal.star.bnl.gov/STAR/starnotes/public/sn0493*

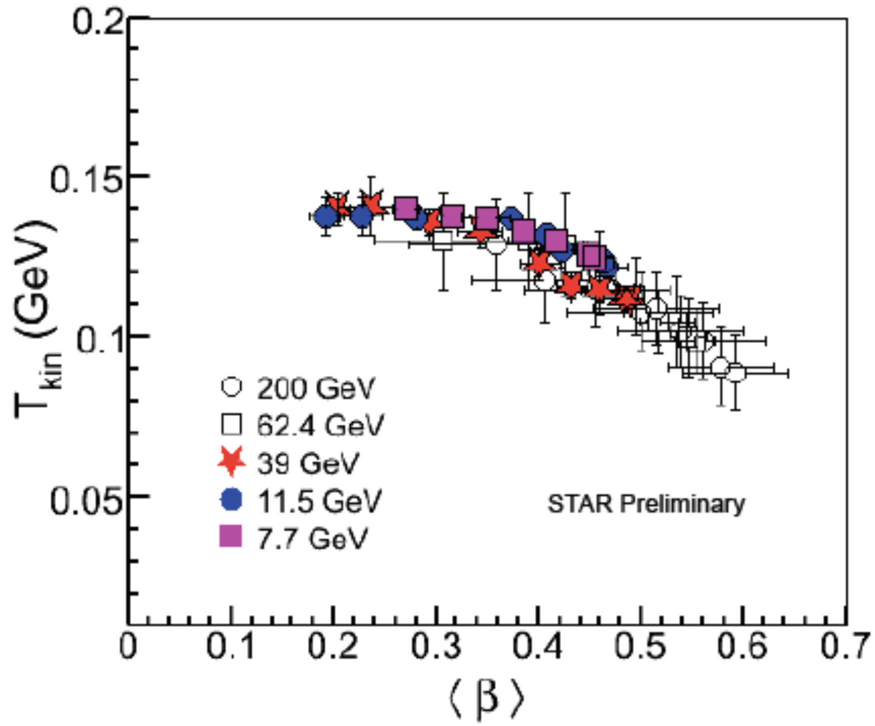
- *arXiv:1007.2613*

STAR Hadron Spectra



(1) Bulk Properties at Freeze-out





Chemical Freeze-out: (GCE)

- Central collisions => higher values of T_{ch} and μ_B!
- The effect is stronger at lower energy.

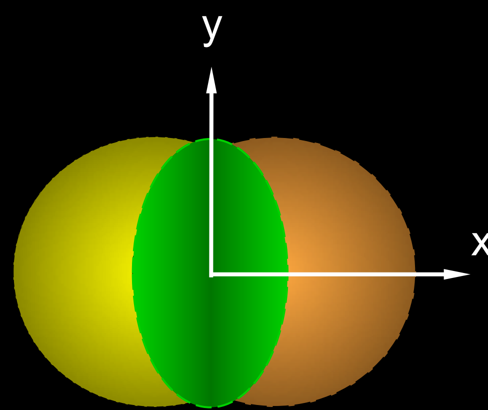
Kinetic Freeze-out:

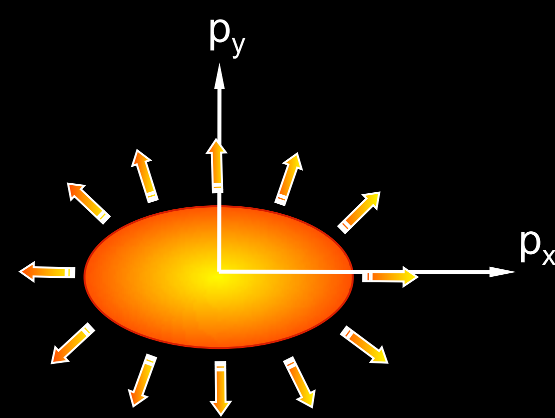
- Central collisions => lower value of T_{kin} and larger collectivity β
- Stronger collectivity at higher energy

STAR: S. Das, L. Kumar, QM2012

Anisotropy Parameter v_2

coordinate-space-anisotropy ➪ momentum-space-anisotropy

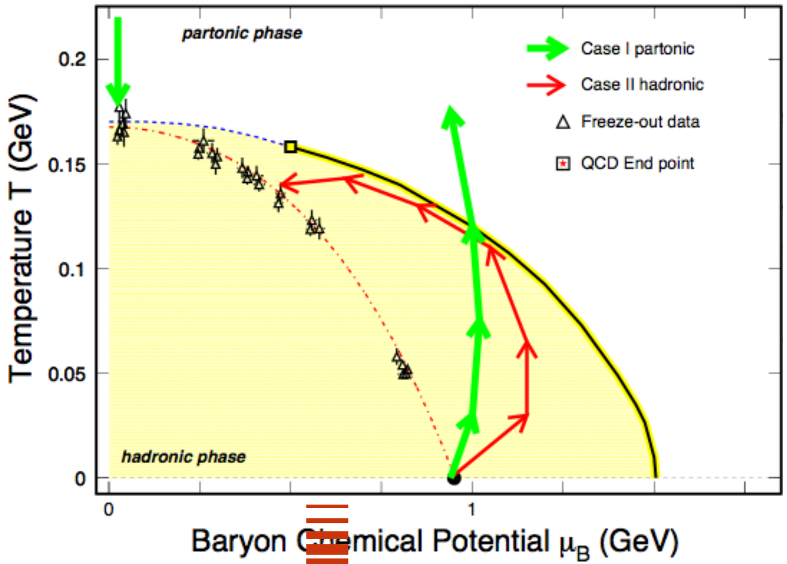


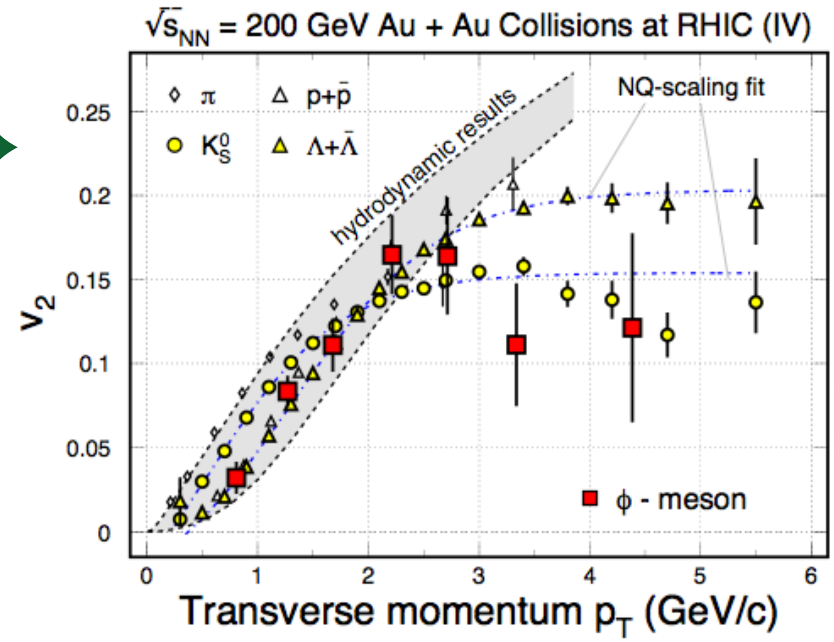


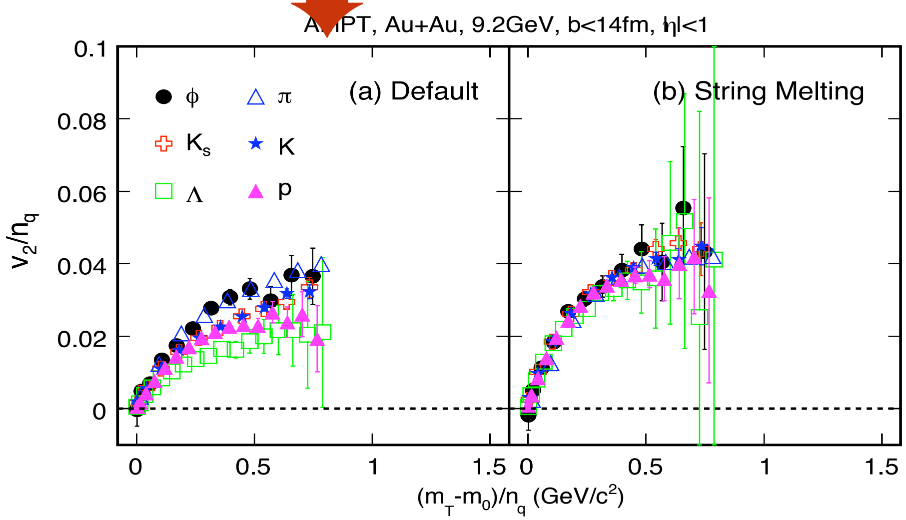
$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle \cos 2\varphi \rangle, \quad \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

Initial/final conditions, EoS, degrees of freedom

(3) NCQ Scaling in v_2





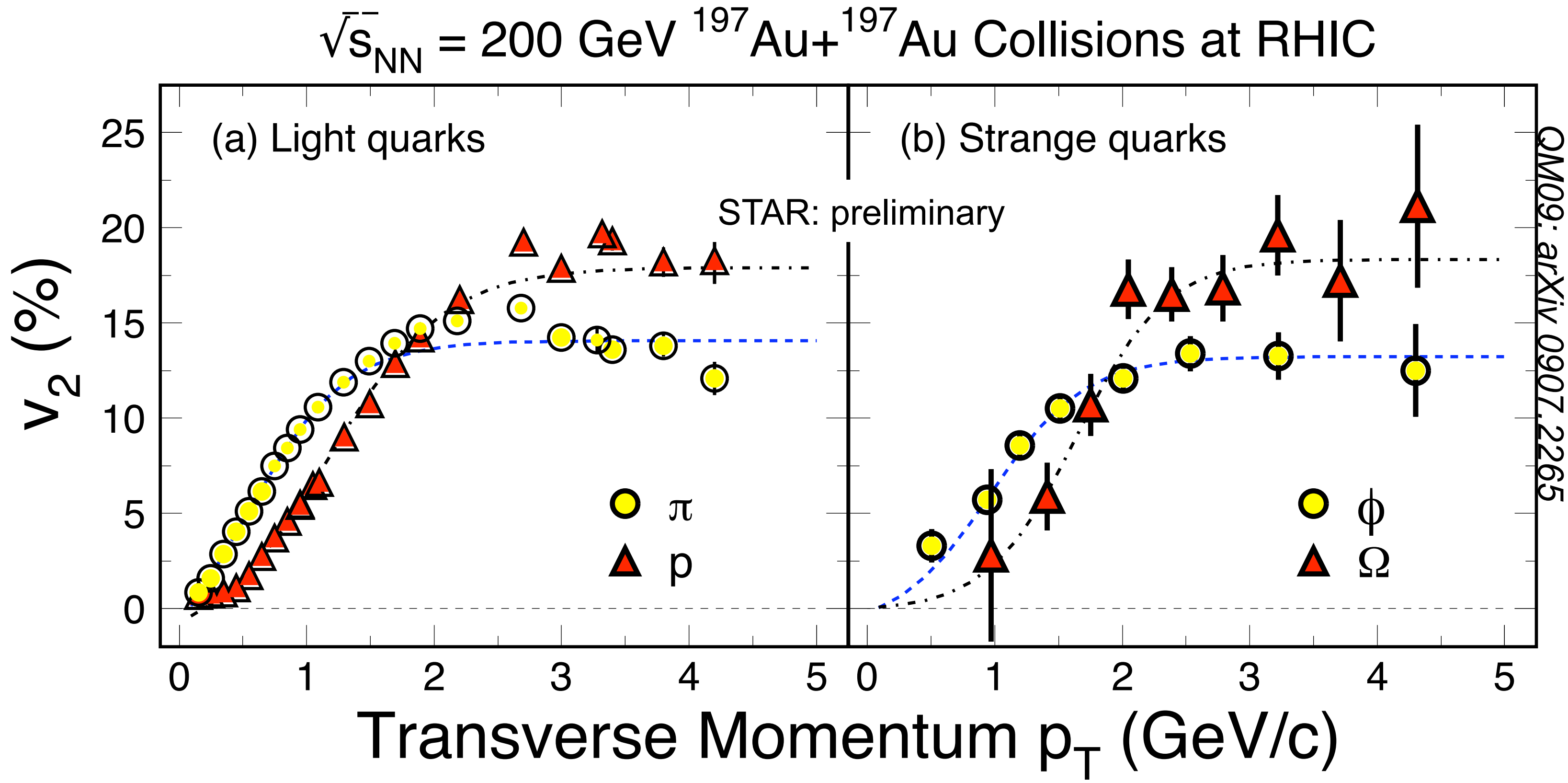


- $m_\phi \sim m_p \sim 1$ GeV
- ss ⇨ φ not K^+K^- ⇨ φ
- $\sigma_{\phi h} << \sigma_{p\pi,\ \pi\pi}$

In the hadronic case, no number of quark scaling and the value of v_2 of φ will be small.

*** Thermalization is assumed!**

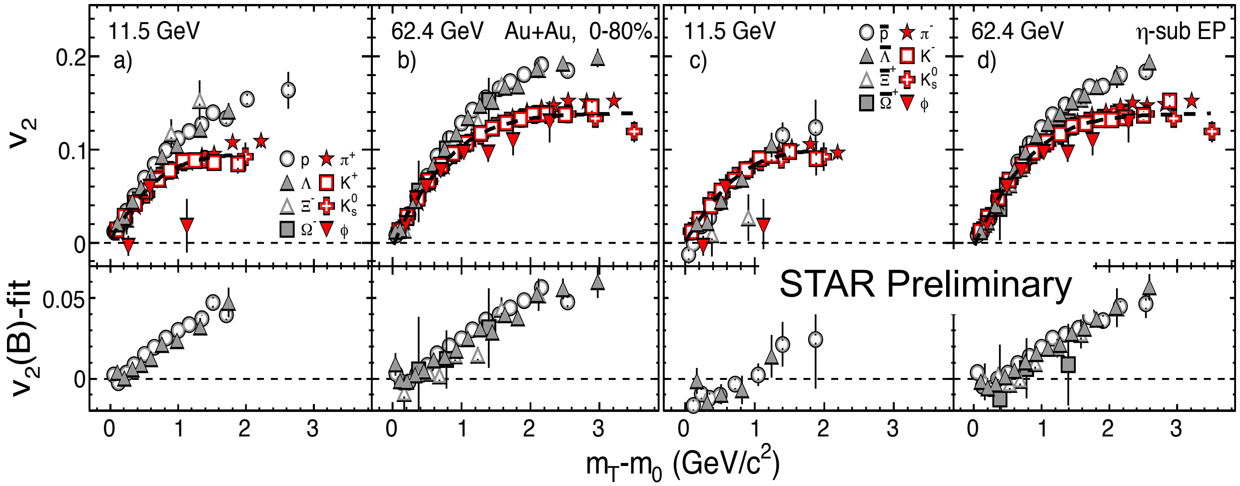
Partonic Collectivity at RHIC

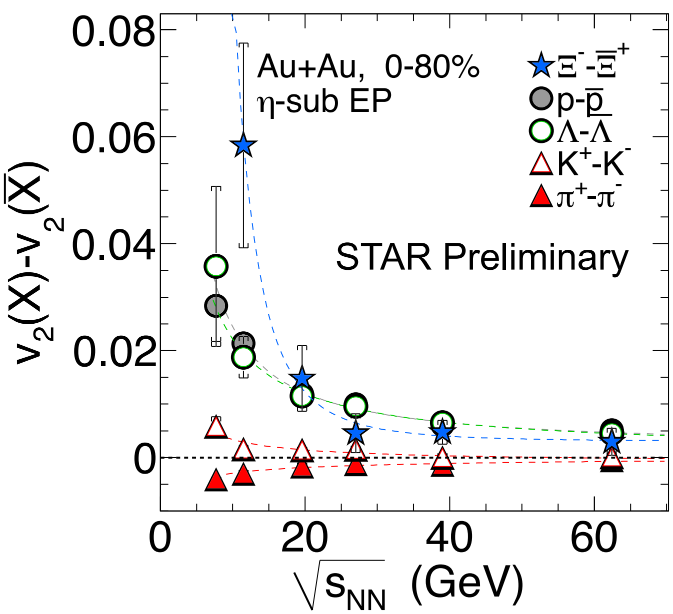


Low p_T (≤ 2 GeV/c): hydrodynamic mass ordering
High p_T (> 2 GeV/c): ***number of quarks scaling***

➔ ***Partonic Collectivity, necessary for QGP!***
➔ ***De-confinement in Au+Au collisions at RHIC!***

Collectivity v_2 Measurements



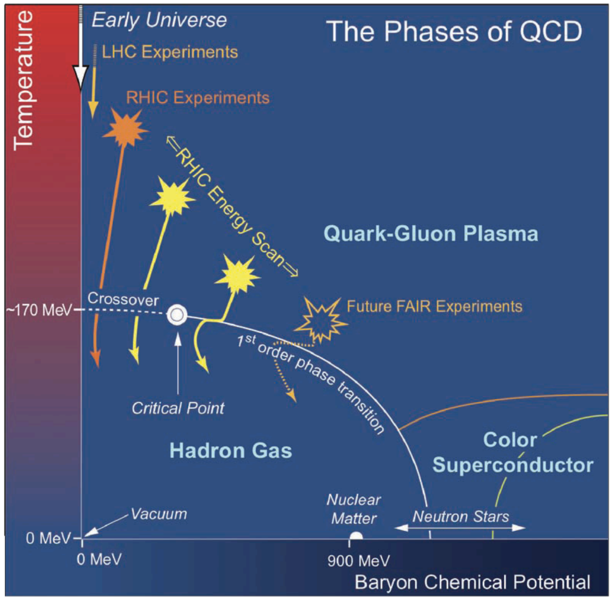


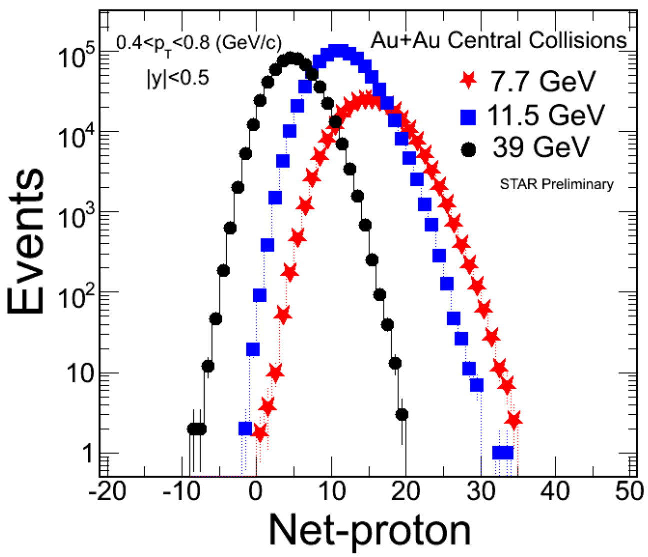
1) Systematic measurements of collectivities

2) Number of quark scaling is broken. Hadronic interactions become dominant, especially for $\sqrt{s_{NN}}$ < 11.5 GeV

STAR: S.S. Shi, QM2012

(5) Higher Moments





1) High moments for conserved quantum numbers: ***Q, S, B***, in high-energy nuclear collisions

2) Sensitive to critical point (ξ correlation length):

$$\left\langle (\delta N)^2 \right\rangle \approx \xi^2, \ \left\langle (\delta N)^3 \right\rangle \approx \xi^{4.5}, \ \left\langle (\delta N)^4 \right\rangle \approx \xi^7$$

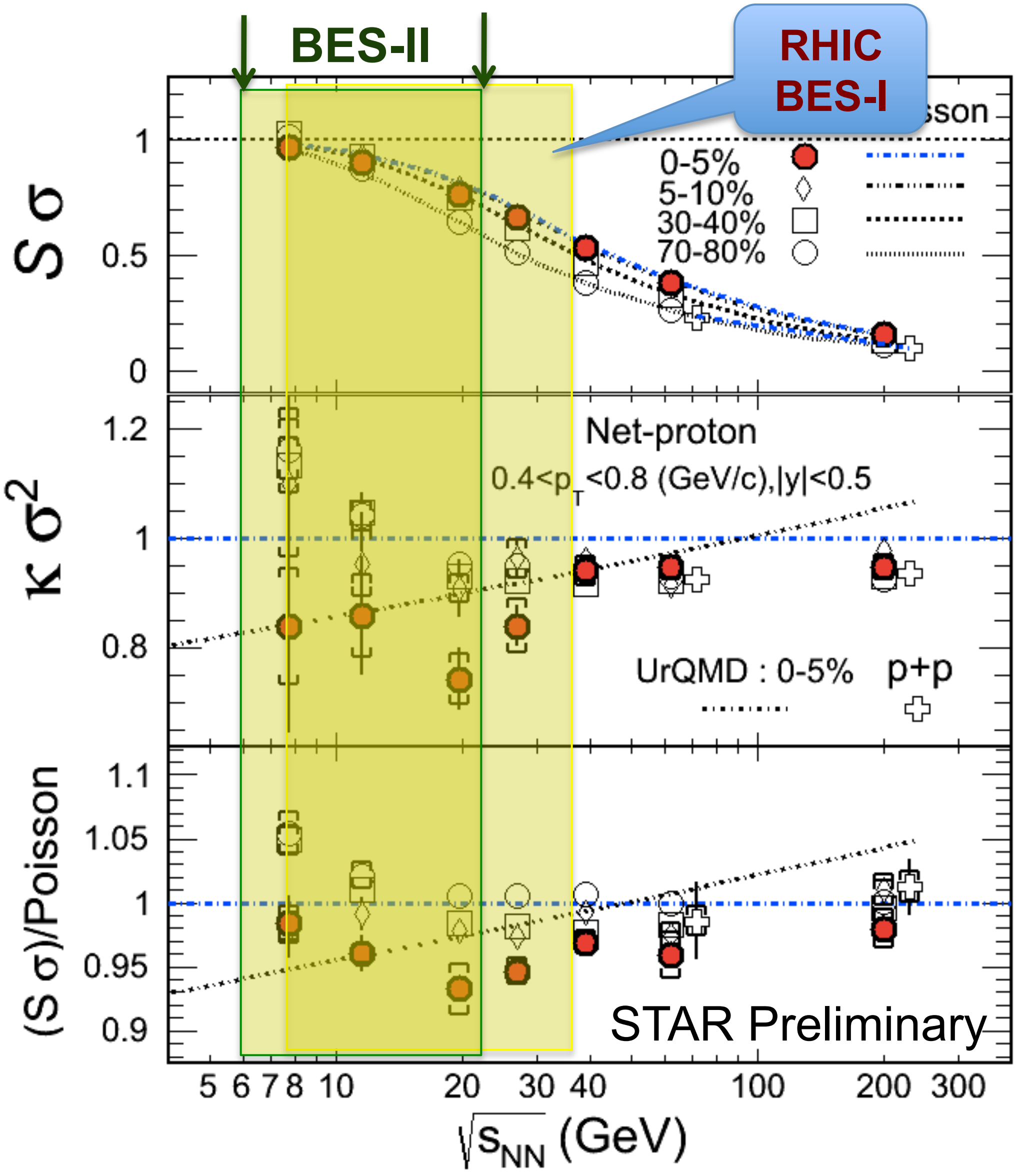
3) Direct comparison with Lattice results:

$$S*\sigma \approx \frac{\chi_B^3}{\chi_B^2}, \qquad \kappa*\sigma^2 \approx \frac{\chi_B^4}{\chi_B^2}$$

4) Extract susceptibilities and freeze-out temperature. An independent/important test on thermal equilibrium in heavy ion collisions.

- A. Bazavov et al. *1208.1220* (NLOTE)
- STAR Experiment: *PRL*105, 22303(2010)
- M. Stephanov: *PRL*102, 032301(2009)
- R.V. Gavai and S. Gupta, *PLB696*, 459(2011)
- S. Gupta, et al., *Science*, 332, 1525(2011)
- F. Karsch et al, *PLB695*, 136(2011)
- M.Cheng et al, *PRD79*, 074505(2009)
- Y. Hatta, et al, *PRL91*, 102003(2003)

Net-proton Higher Moments



STAR net-proton results:

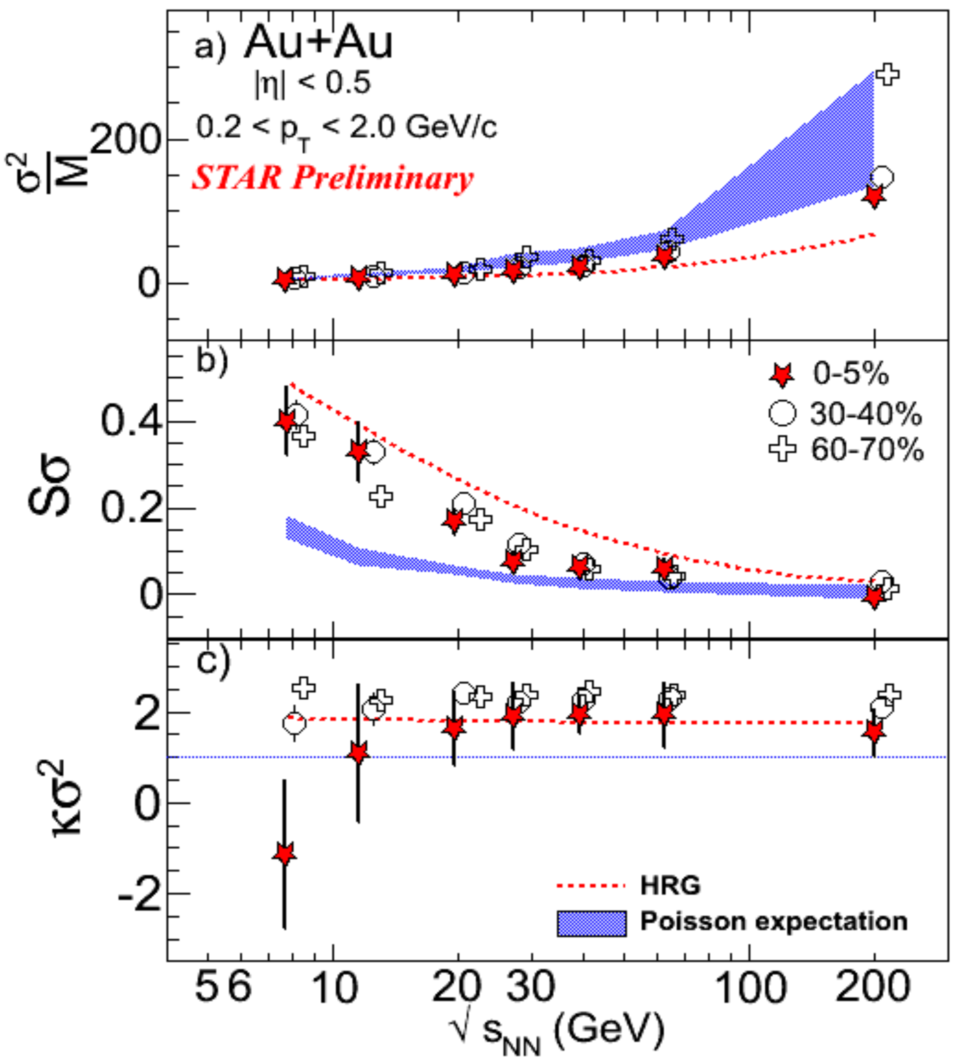
1) All data show deviations below Poisson beyond statistical and systematic errors in the 0-5% most central collisions for $\kappa\sigma^2$ and $S\sigma$ at all energies. Larger deviation at $\sqrt{s_{NN}} \sim$ 20GeV.

2) UrQMD model show monotonic behavior in the moment products.

3) Higher statistics needed for collisions at $\sqrt{s_{NN}} <$ *20 GeV.*

- STAR: X.F. Luo, QM2012

Higher Moment: Net-charge



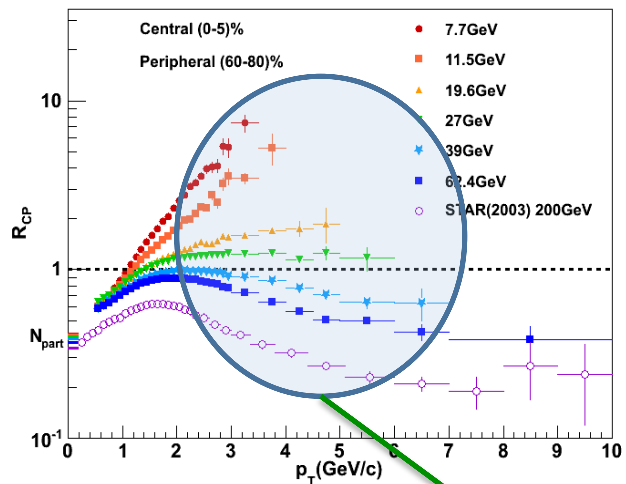
1) Preliminary net-charge results: efficiency, decay, … effects under study.

2) Higher statistics data needed below 20 GeV.

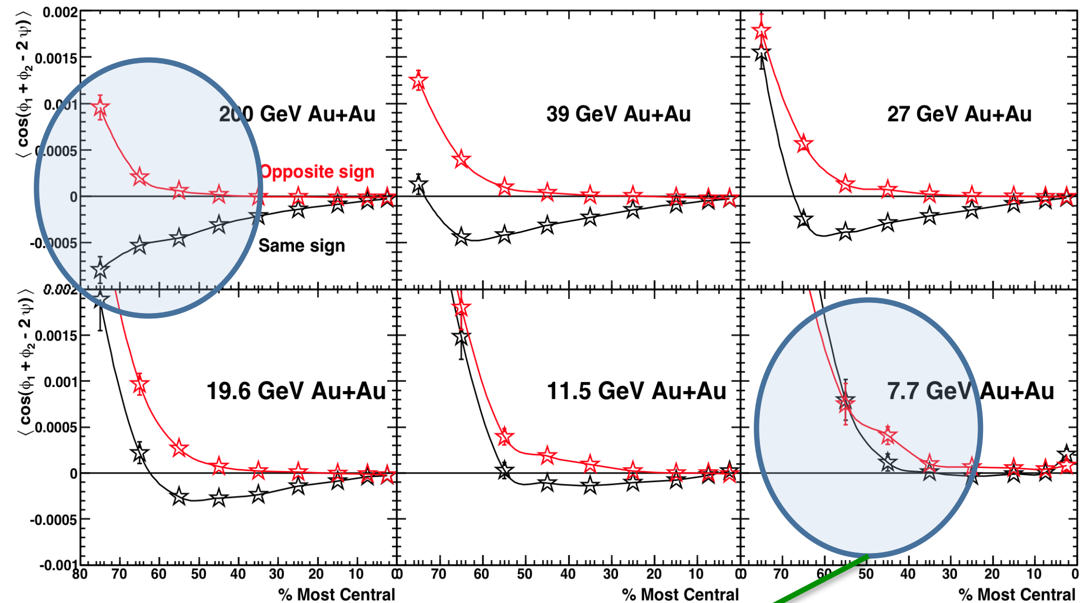
- STAR: D. McDonald, QM2012
- K. Redlich et al, private communications

RHIC BES-I Highlights

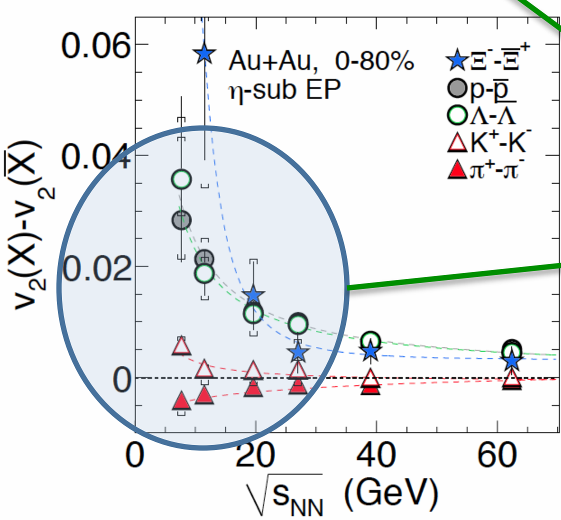
(3) Jet-quenching



(5) "Local Parity Violation"



(4) NCQ Scaling in v_2



sQGP key signatures

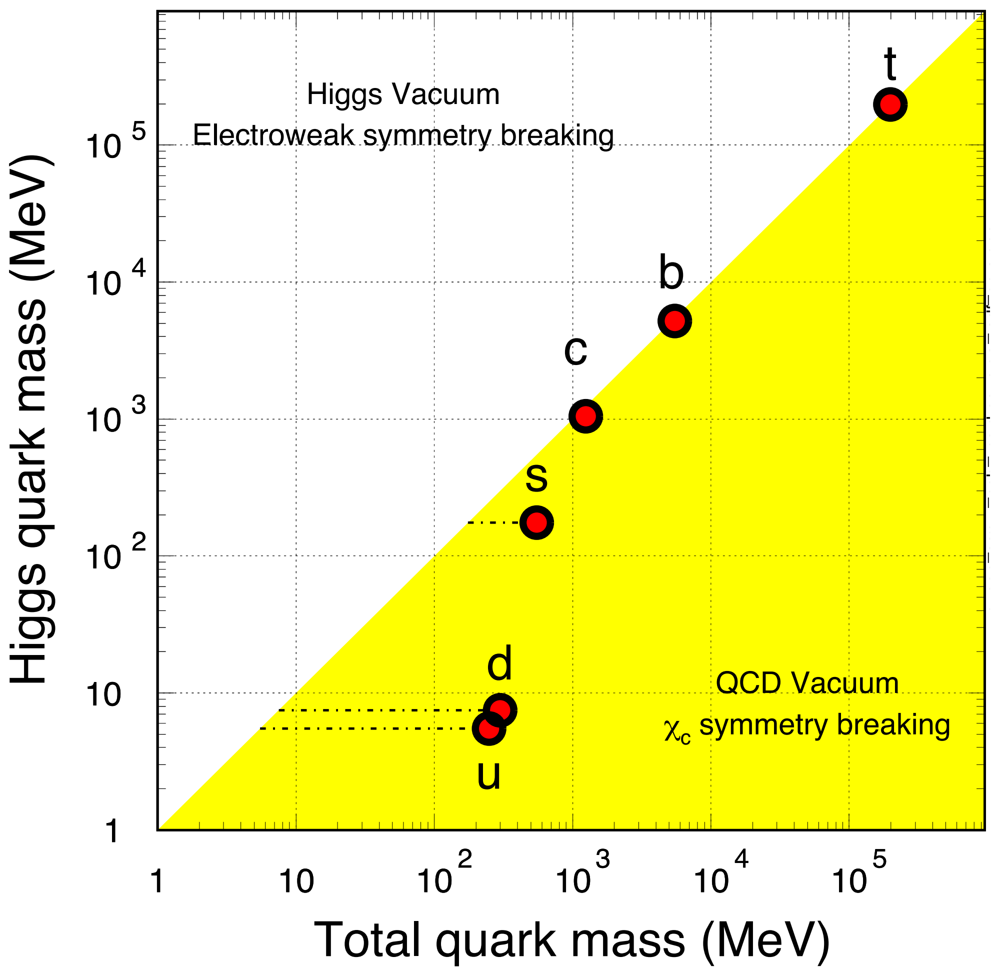
turned off!

The results from BES-I not only identified the region where hadronic interactions are dominant. In turn, it demonstrates the existence of the partonic matter, the quark-gluon plasma (QGP), in the region at vanishing baryon chemical potential.

Heavy Quark Productions In High-Energy Nuclear Collisions

- Open heavy quark hadron productions
- Quarkonia productions

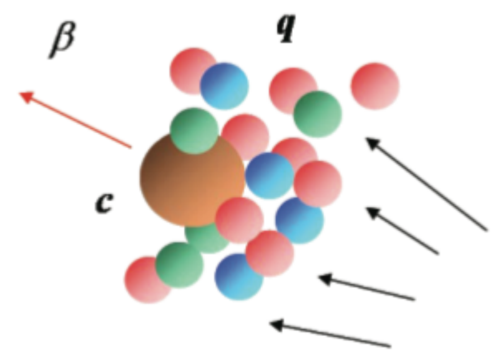
Why Heavy Quark?



- Heavy quark masses are not altered in QCD medium
- Negligible thermal production in collisions due to their heaviness

➢ Too for studying properties of the hot/dense medium at the early stage of high-energy collisions

Heavy quark collectivity => Light flavor thermalization



X. Zhu, *et al,* PL**B647**, 366(2007)

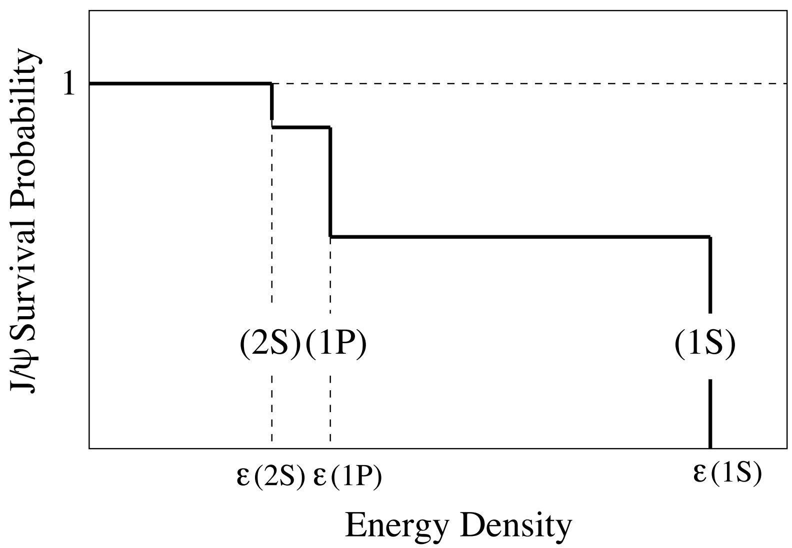
In Nucleus-Nucleus Collisions

Sequential Suppressions

Debye Screening:

$$J/\psi \rightarrow c + \bar{c} \qquad r_{J/\psi} \geq \lambda_D \approx \frac{1}{g(T) \bullet T}$$

1) Total # of J/ψ reduces
2) Sensitive to initial scattering



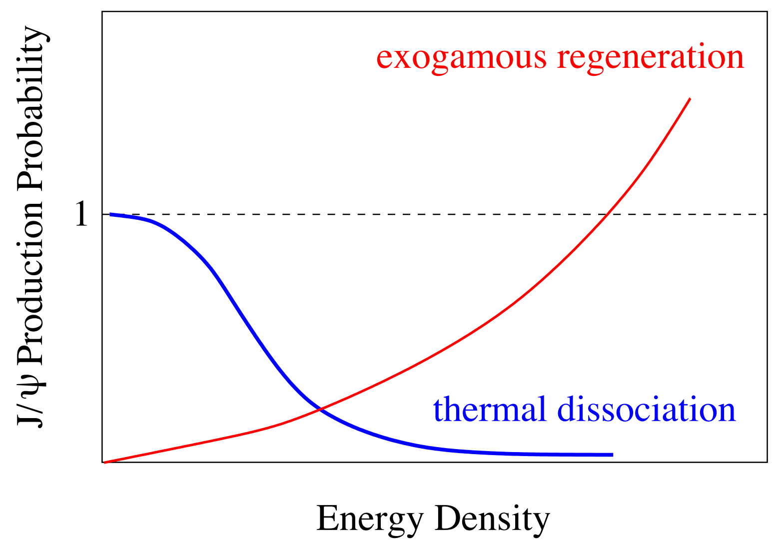
Matsui & Satz, PL**B178**, 178(1986).

Regenerations

At the boundary of hadronizatipn:

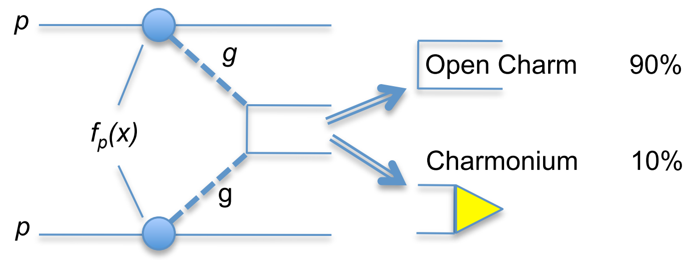
$$c + \bar{c} \rightarrow J/\psi$$

1) Total # of J/ψ increases
2) Sensitive to hot/dense medium



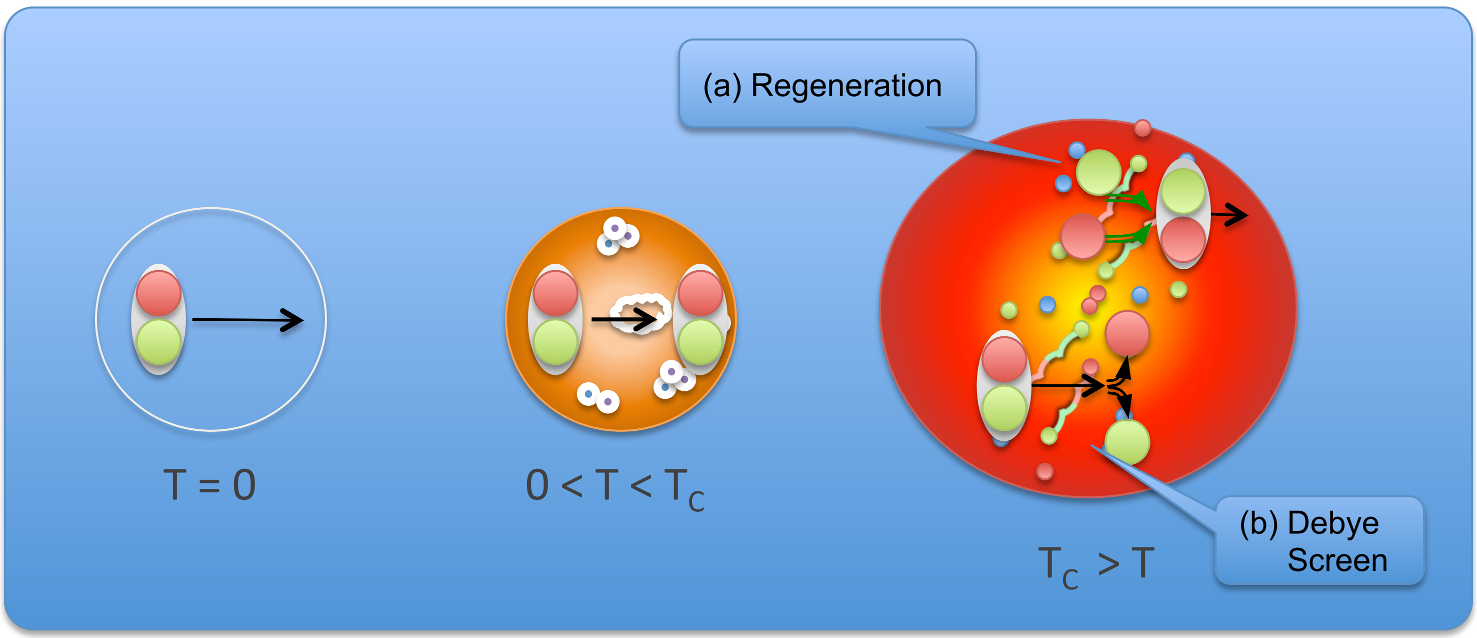
Quarkonium Production

p + *p* Collisions

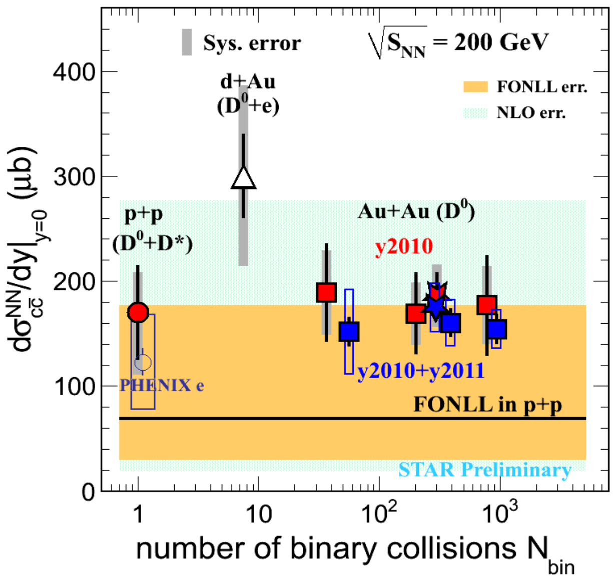


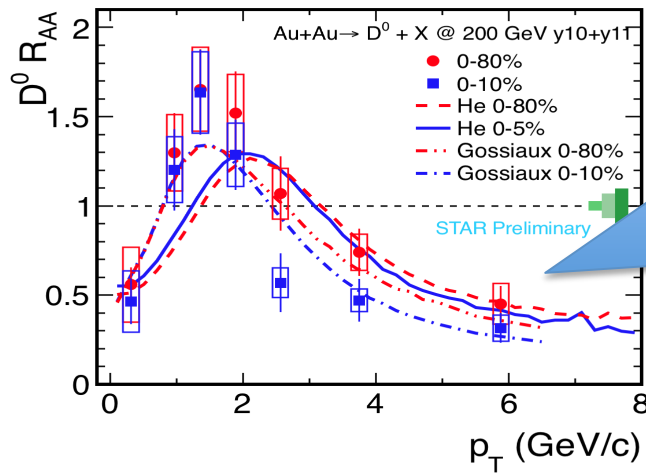
Heavy Ion Collisions

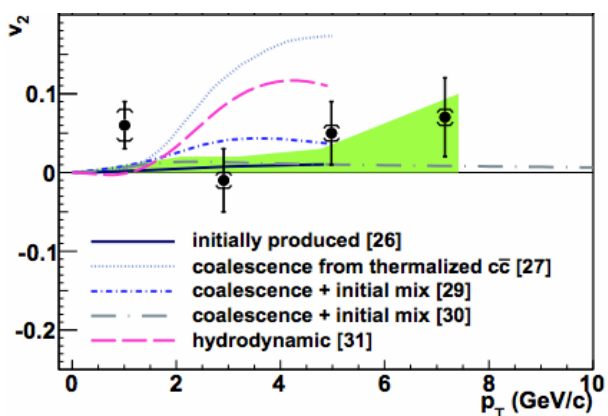
1) *Npdf:* Initial condition
2) *Cronin effect:* CNM effect
3) *Debye Screen:* hot/dense medium
4) *Regeneration:* hot/dense medium

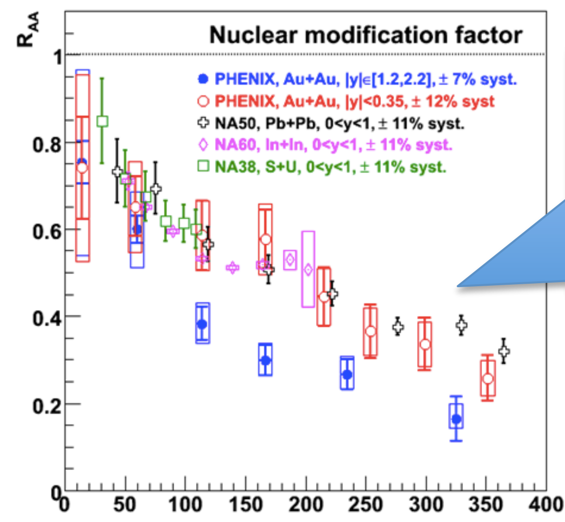


Charm Production at RHIC









Open Charm:

(1) Initial production follows binary collisions

(2) Suppressed at p_T> 3GeV/c.

J/ψ: (closed Charm)

(1) suppressed in more central collisions. Similar observations at LHC

(2) Near zero v_2.

QM 2011, QM 2012

TMD: J/ψ $R_{AA}(p_T)$!

Modification Factors

$$R_{AA} = \frac{\langle N \rangle^{AA}}{n_{bin}^{AA} \langle N \rangle^{pp}}$$

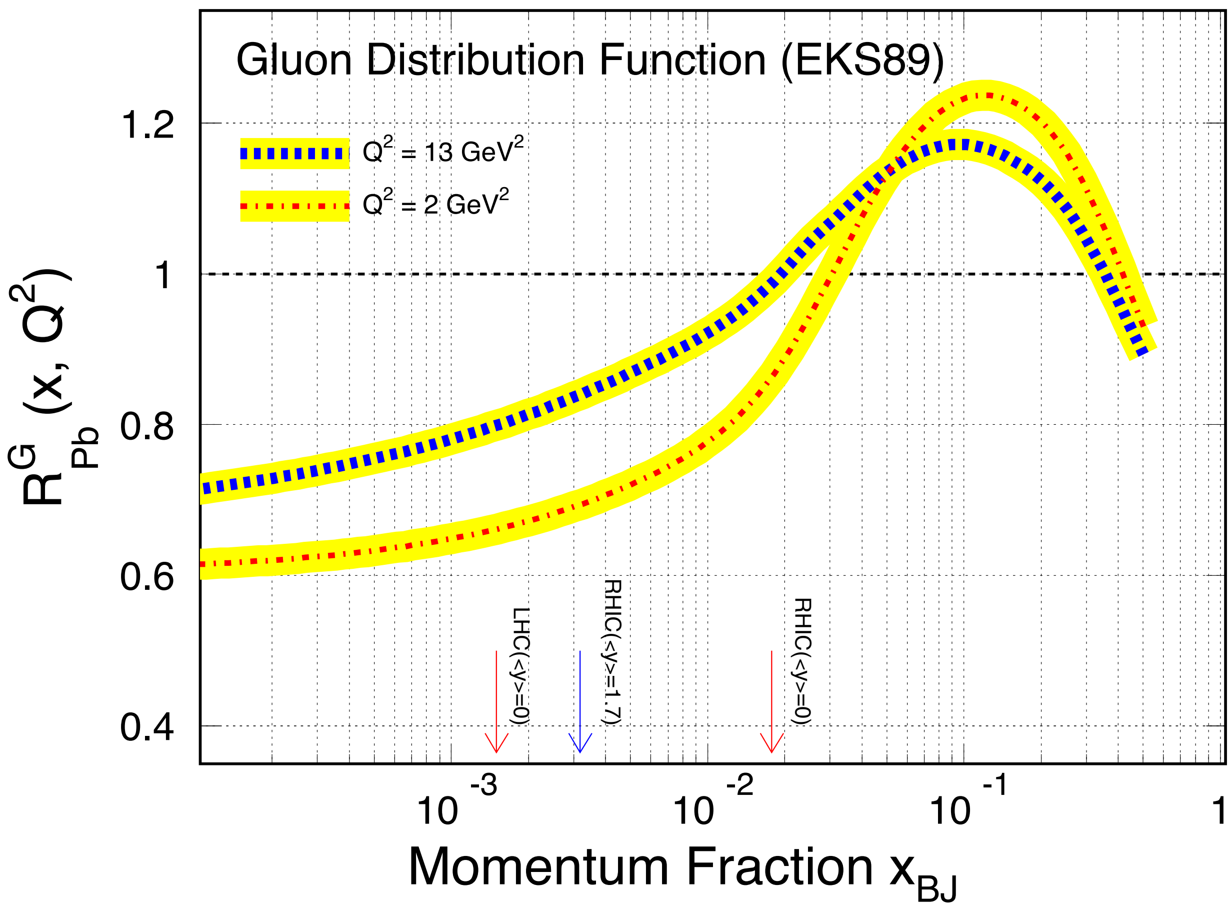
1) Traditional R_{AA} depends on the TMD p_T integrated yields. Sensitive to *Npdf** and model dependent parameter n_{bin}.

$$r_{AA}(p_T^2) = \frac{\langle p_T^2 \rangle^{AA}}{\langle p_T^2 \rangle^{pp}}$$

2) The TMD dependent $r_{AA}(p_T)$ sensitive to medium effect including Cronin scattering, Debye Screening, and regeneration**.

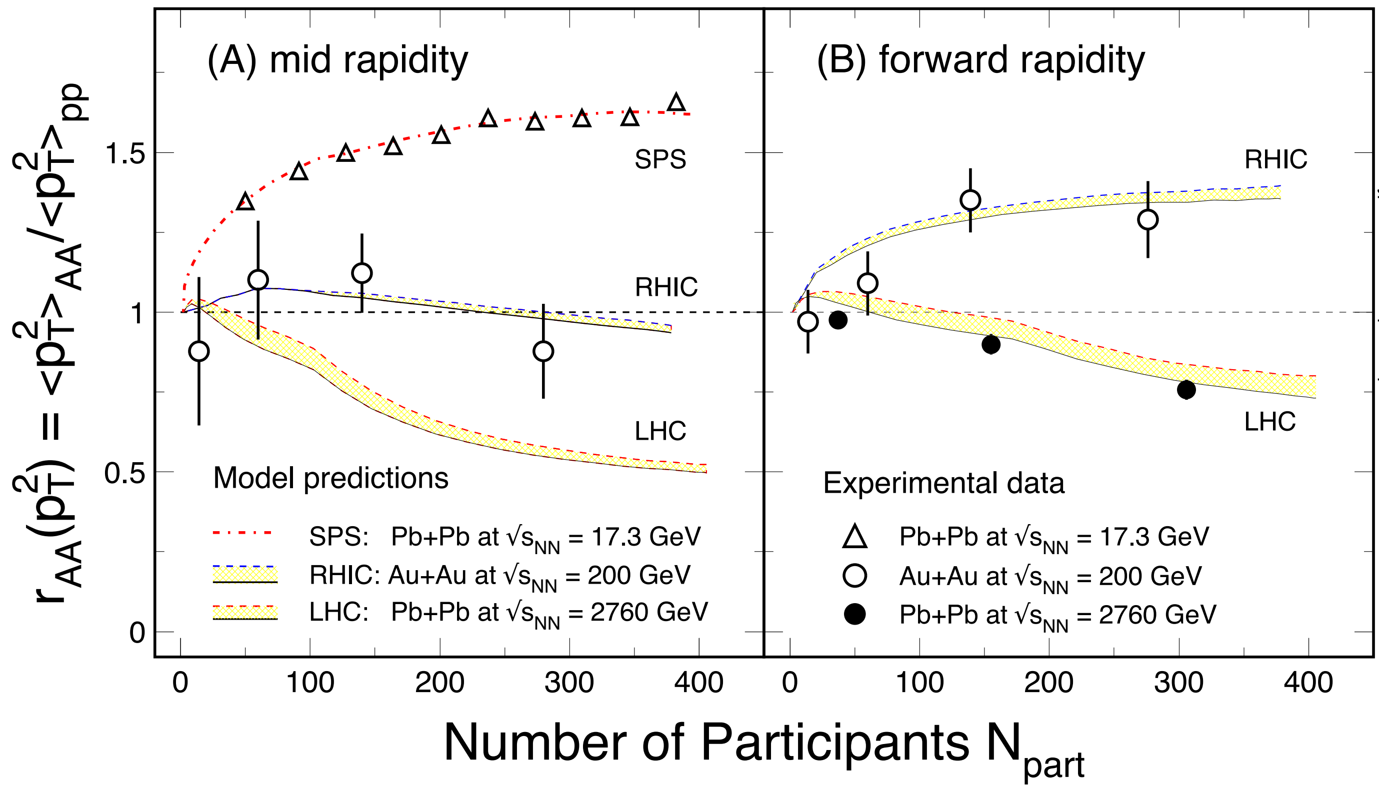
* H. Satz arXiv: 1303.3493
** Pengfei Zhuang et al, 2010

Parton Distribution Function



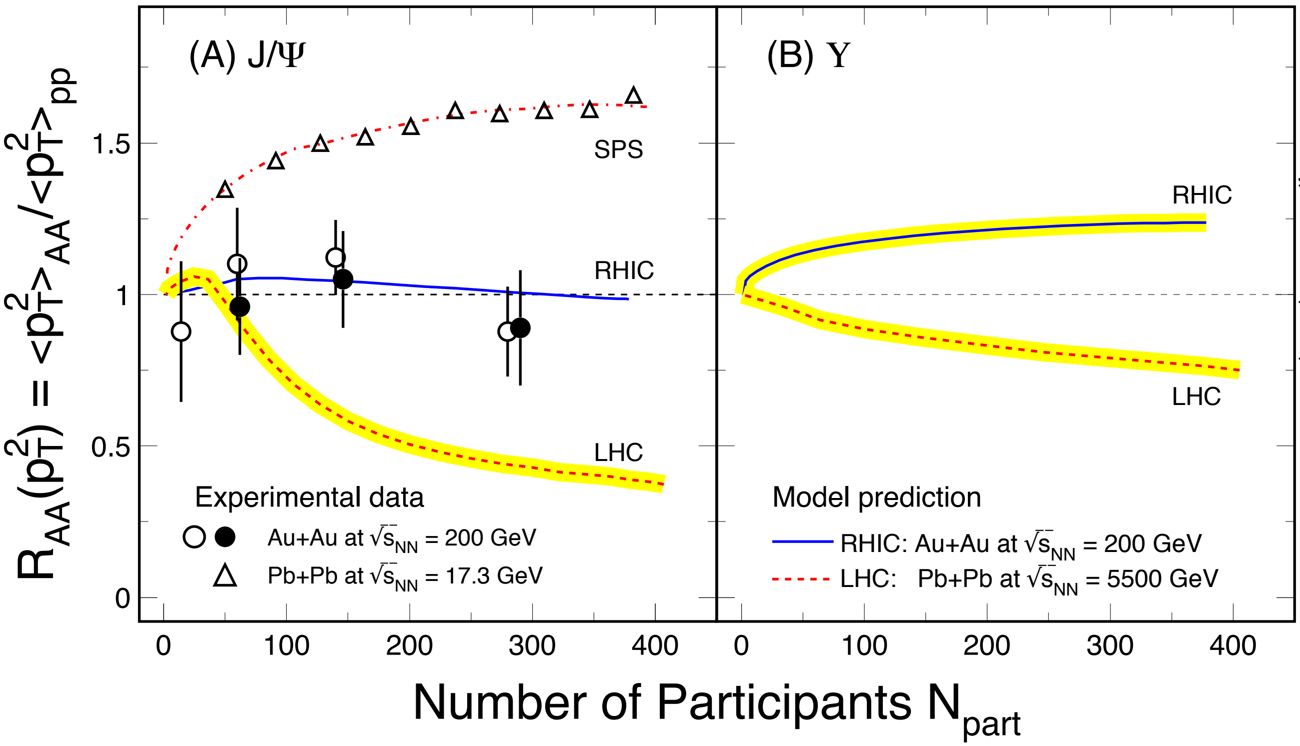
1) Nucleon parton distribution function. Due the non-linear dynamic at small-x, the nuclear parton distribution is different.
2) Different experiments at different x leads to different parton flux.

T.M.D.: Charmonium Production



1) **LHC:** more final *J/ψ*s produced via regeneration leads to lower value of $<p_T>$
2) **SPS:** all final *J/ψ*s are survival ones. The increase of $<p_T>$ is due to the initial Cronin scatterings
3) **RHIC:** mixture of initial and regenerated *J/ψ*s

T.M.D.: Quarkonia Production



(A) *J/ψ* productions at SPS, RHIC and LHC

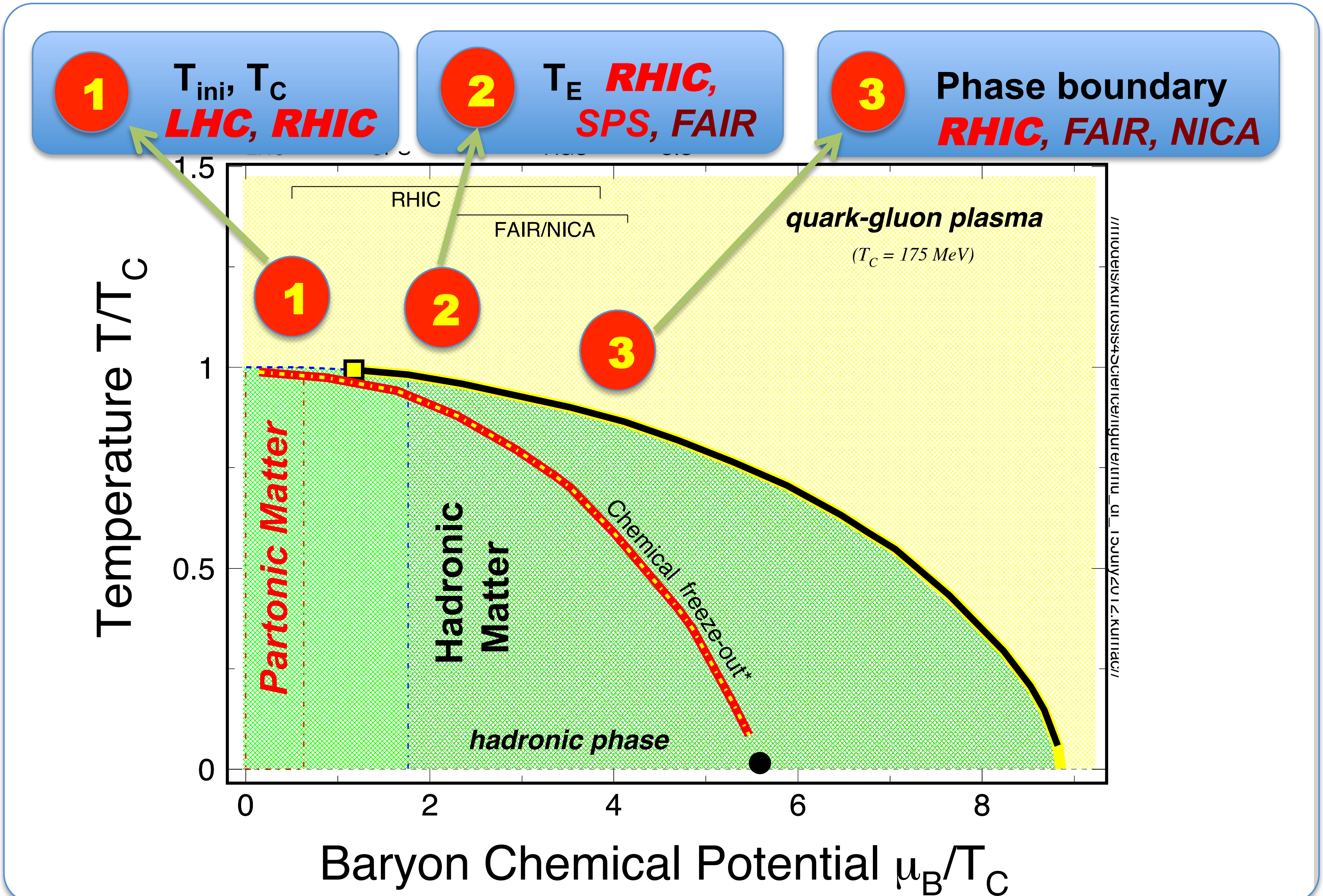
(B) Prediction of *Upsilon* production: Due to small bottom cross section at RHIC, negligible regenerations, Cronin effect is dominant. At LHC, sizable contributions from regenerations. A prediction!

T.M.D. Summary

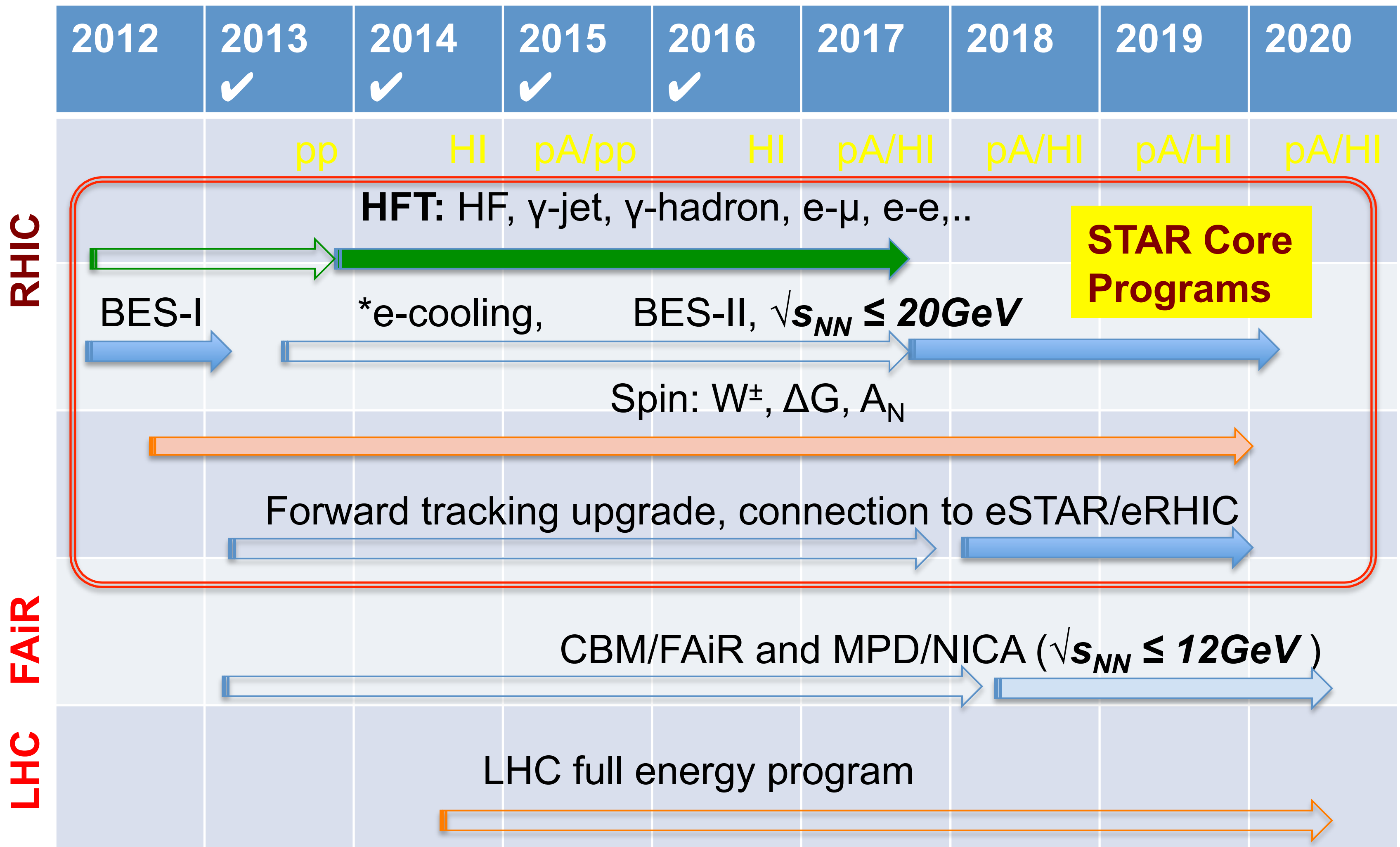
(1) The effects of Debye Screening and Regeneration are opposite for quarkonia production. They are all medium effects.

(2) J/ψ productions, shown by **r_{AA}**(p_T), clearly demonstrated the influence of regeneration implying the formation of the hot/dense medium, the QGP, at RHIC and LHC.

Exploring QCD Phase Structure



Facilities for QCD Matter Study



More involvements in future upgrade programs!

Summary

1) BES Program:

- Partonic QGP dominant: $\sqrt{s_{NN}}$ **> 39 GeV**
  Hadronic interactions become dominant: $\sqrt{s_{NN}}$ **≤ 11.5 GeV**

- High statistics data for energy region $\sqrt{s_{NN}} \leq 20$ GeV,
  needs e-cooling at RHIC

2) Heavy Flavor and Di-lepton Programs:

STAR HFT+MTD upgrades ready by summer of 2013

RHIC: **Unique opportunities for exploring QCD phase structure**